Energy 288 (2024) 129622

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Analyzing the global warming potential of the production and utilization of lithium-ion batteries with nickel-manganese-cobalt cathode chemistries in European Gigafactories

Mehrshad Kolahchian Tabrizi, Davide Bonalumi *, Giovanni Gustavo Lozza

Department of Energy - Politecnico di Milano, Via Lambruschini 4, 20156, Milano, Italy

ARTICLE INFO

Handling Editor: Prof X Ou

ABSTRACT

This study evaluates the global warming potential (GWP) impact of producing lithium-ion batteries (LIBs) in emerging European Gigafactories. The paper presents a cradle-to-gate (CTG) life cycle assessment (LCA) of nickel-manganese-cobalt (NMC) chemistries for battery electric vehicle (BEV) applications. We consider three scenarios to cover the most probable production routes in Germany, France, and Italy, foreseen as the largest European LIB producers by 2030. The energy demand for manufacturing considers two cases: electricity only and a mix of heat and electricity. The results show that European Gigafactories can reduce the overall GWP relative to 1 kWh of NMC battery, with respect to Chinese NMC LIBs, in a range of 32–60%. This corresponds to a decrease in equivalent CO_2 emission of 32–81 kg CO_2 eq., depending on the location, the energy demand and the NMC chemistry, if the whole production takes place in the facility. French Gigafactories obtain the upper bound of this reduction. A sensitivity analysis of the source of the lithium compound, used to produce the active cathode material, shows that increasing the nickel content decreases the GWP impact per kWh of battery capacity. However, NMC622 generates less equivalent CO_2 than NMC811, for lithium compound produced from Chilean brine. In addition, a simplified analysis of the utilization phase of two different classes of BEVs shows the positive effects of the regional LIB production and of the low carbon intensity of the electricity mix.

Credit author statement

Davide Bonalumi: Conceptualization, Methodology, Investigation, Formal analysis, Validation, Visualization, Writing- Reviewing and Editing, Resources, Supervision, Mehrshad Kolahchian Tabrizi: Data curation, Investigation, Methodology, Software, Formal analysis, Visualization, Writing – original draft preparation, Writing- Reviewing and Editing, Giovanni Gustavo Lozza: Resources, Visualization, Reviewing and Editing, Supervision

1. Introduction

Battery electric vehicles (BEVs) are foreseen as a substitution for conventional internal combustion vehicles (ICEVs) to reduce exhaust emissions [1]. Spreading BEVs with phasing out of ICEVs, while decarbonizing electricity generation, is a popular solution to decrease well-to-wheel (WTW) GHG emissions [2,3]. BEVs are free of direct tailpipe emissions, but GHG emissions and other environmental impacts linked to electricity supply and vehicle manufacturing may be significant [4]. In recent years, high efficiency, longer life cycle and high energy density characteristics made the lithium-ion-batteries (LIBs) the primary choice to power mobile applications [5,6]. Major LIB producers are located in Asia [7], where China has been the largest power battery producer worldwide with the 77% of the global LIB production capacity in 2020 (350 GWh) [8,9]. In recent years, the U.S. and Europe planned or commissioned several large LIB production facilities to decrease the dependency on Asian suppliers [10]. Their production capability of several GWh/year justifies the name "Gigafactory" after the Tesla Gigafactory 1 in Nevada, USA [11]. These large-scale LIB production plants secure the LIB supply for BEV producers and minimize transportation

Abbreviations: ADP, abiotic depletion; AP, acidification; BEVs, Battery Electric Vehicles; BOM, Bill of Material; CTG, Cradle-to-Gate; GWP, Global Warming Potential; HTP, human toxicity; ICE, Internal Combustion Engine; ICEVs, Internal Combustion Engine Vehicles; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LIBs, Lithium-ion Batteries; NMC, Nickel–Manganese–Cobalt; WTW, Well-to-Wheel.

* Corresponding author.
E-mail address: davide.bonalumi@polimi.it (D. Bonalumi).

https://doi.org/10.1016/j.energy.2023.129622
Received 2 August 2023; Received in revised form 6 October 2023; Accepted 8 November 2023
Available online 20 November 2023

efforts and costs.

Production of LIBs is subjected to a considerable number of environmental impacts, such as abiotic depletion (ADP), acidification (AP) and human toxicity (HTP) sourced by the material and the energy usage [6]. The global warming potential (GWP) impact has high relevance to the goals for the decarbonization of the transportation sector. The energy demand of the LIB production generates a part (sometimes neglected …) of the GWP impact. The facility's production capacity and its throughput mainly affect the energy intensity for cell production [12]. Most of the LCA studies on LIB production before 2019 considered lab-scale or MWh (not GWh) production capacities. Majeau-Bettez et al. [13] found the overall GWP impact of the production of 1 kWh of NMC and LFP batteries, considering an average European electricity mix, in a range of 200–250 kg CO_2 eq. Their life cycle inventory (LCI), a collection of data related to material, energy, and water consumption and process emissions, was based on a lab-scale nickel manganese cobalt oxide (NMC) powder production, assuming material inputs on stoichiometric calculations and energy inputs on engineering calculations [12]. Ellingsen et al. [14] presented a very detailed inventory of NMC batteries based on their own primary data and ecoinvent 2.2, as one of the most used databases worldwide [15]. The NMC111 ($LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$) battery produced in South Korea and assembled in Norway resulted in a GWP equal to 172 kg CO_2 eq. per kWh. Their primary data for energy consumption accounts for 70 MWh annual cell production capacity [16]. Kim et al. [17] reported the GWP of a mass-produced commercial LIB in South Korea and packed in the U.S. equal to 140 kg CO_2 eq. per kWh, where the cell production site was underutilized [12] and only 56 MWh of production capacity was exploited [18]. Therefore, none of these studies presents a LIB Gigafactory that works at its designed capacity throughput.

The energy demand and corresponding environmental impacts of LIB production facilities with Giga-scale capacity, working at full throughout, are assessed in more recent studies. Dai et al. [12] reported a GWP equal to 72.9 kg CO_2 eq. per kWh of NMC111 battery, based on the primary data from a leading Chinese cathode material producer with a 2 GWh production capacity and on the Argonne National Laboratory's "Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET)" model [19]. Sun et al. [8] studied the environmental impacts of NMC622 production in a Chinese LIB manufacturer with a 30 GWh production capacity, which resulted in an overall GWP equal to almost 125 kg CO_2 eq. per kWh excluding the end-of-life stage. Production of NMC811 cells in a facility working in South Korea or Sweden with a 16 GWh production capacity is process-simulated by Chordia et al. [16]. Their cradle-to-gate LCA based on conservative process simulations showed GWP impacts equal to 104 and 50 kg CO_2 eq. per kWh, according to the carbon intensity of the production location's electricity mix. Kelly et al. [20] performed an LCA for the production of NMC111 in different regions of the world, including Europe and China. They reported a 65 kg CO_2 eq. per kWh for a European-dominant supply chain. A part of the authors of Kelly et al. [20] presented a similar work to the later publication in Winjobi et al. [21], expanding the scope of their analysis to the NMC cathodes family. Both references utilized the GREET model to perform their LCA, therefore, the energy consumption for cell production is similar to the work of Dai et al. [12], who obtained their data from a GWh-scale cathode material producer. Recently, Bonalumi and Kolahchian Tabrizi [22] proposed a unified LCI based on the GREET model and the Chinese battery industry production paths for NMC111, considering two energy demand scenarios for LIB manufacturing in Giga-scale capacities. They reported that the overall GWP could vary from 89 to 169 kg CO_2 eq. per kWh, depending on the lithium source, manufacturing scenario, and the Bill of Material (BOM).

Manufacturing energy usage has been one of the main sources of discrepancies in the LIB LCA literature over the last two decades [6]. Fortunately, the published literature in recent years shows a consensus range for estimating the LIB plants' energy usage. Kurland [23] estimated the energy demand for LIB cell manufacturing, based on the technical reports from Swedish Northvolt Ett with an 8 GWh annual capacity (the first production line of four planned ones) and from Tesla Gigafactory 1 in Nevada with a capacity of 35 GWh. He reported the energy use of these two facilities in a range of 50–65 kWh of electricity to produce 1 kWh of cell capacity, excluding mining and material processing. The cell manufacturing model developed by Jinasena et al. [24] showed the total energy requirement for the NMC LIB family to be in the range of 38–51 kWh/kWh_{cell}. Degen and Schütte [25] determined the energy consumption of a German research factory with 7 GWh/year electrode output based on the machine specifications as 41.48 kWh to produce 1 kWh of battery cell, almost equally supplied by electricity and natural gas.

In this Journal, *Energy*, some articles studied Well-to-Wheel emission of BEVs and conventional ICEVs, covering only the carbon footprint related to electricity or fuel supply and vehicle consumption [26–28]. A few authors expanded the scope of their study also to vehicle manufacturing, specifically LIB production impact [29–34]. The mentioned articles did not focus on the production of traction batteries. In other words, they directly adopted the impact of the battery from software or other studies for a Chinese LIB production scenario [29,30,33,34]. Moreover, the research papers available in this Journal (in general, the scientific literature) did not consider the manufacturing of the LIBs in the European Gigafactories with its possible production scenarios.

This paper aims to analyze the GWP impact related to the production of NMC LIBs in Germany, France and Italy, using the open-access GREET model. These three countries will become the largest European LIB producers by 2030 [35]. Three different scenarios are developed to cover the most probable production approach in European LIB Gigafactories. Sections 2.1 and 2.2 explain the LCA methodology and the supply chain scenarios. The results are compared to the calculated GWP values for the equivalent Chinese LIB production from a former work of the authors [22] in Sections 3.1 and 3.2. The effect of different lithium sources is analyzed in Section 3.3. Finally, the utilization phase of a BEV equipped with a LIB produced in one of the specified countries, circulating in the same countries, is studied through a simplified analysis in Section 3.4.

2. Methods

2.1. LCA methodology

Life Cycle Assessment (LCA) is performed based on Standards ISO 14040 and 14044 [36,37] within the open-access GREET 2021 model. The GREET model is a tool to calculate the life cycle impacts of vehicle technologies, fuels, products, and energy systems. The scope of the study is to evaluate the GWP impact of LIBs produced in European Gigafactories within a cradle-to-gate (CTG) system boundary. In the CTG system, the extraction and processing of the needed material and manufacturing of the final product are included. We consider NMC traction batteries as produced in these facilities due to their wide application by the automakers [21,38]. The cell capacity improves by increasing the nickel content in NMC cathodes, and the lower cobalt content of NMC622 ($LiNi_{6/10}Mn_{2/10}Co_{2/10}O_2$) and NMC811 ($LiNi_{8/10}Mn_{1/10}Co_{1/10}O_2$) results in lower battery prices [39]. The drawback of this enhancement is the instability issues due to the reactivity of the cathodes towards the liquid organic electrolyte and any trace of moisture [40]. Also, it can be noted that a secure supply chain of nickel and lithium is needed for these high nickel-content chemistries [41]. In spite of the technical challenges, Ni-rich chemistries are currently the most likely candidates for high-density LIBs [16].

Life Cycle impact assessment is here limited to GWP, even if other environmental impact categories could be more significant [6]. Among European countries, Germany, France, and Italy are selected as the target locations, since they will become the largest European LIB producers by 2030 [35]. We also considered China, as the largest LIB producer [42] and LIB material supplier, to provide a broader comparison. Two functional units are defined in this work: material weight (1 kg) is used to assess the impact of producing battery-grade materials, and battery energy capacity (1 kWh), which translates the final impact of the produced battery into an energy basis.

The electricity mix for each European country is modeled in GREET, based on the International Renewable Energy Agency (IRENA) reports [43–45] and the recent work of Scarlat et al. [46] for data obtained in 2019 to keep consistency. In France, nuclear and hydro are responsible for 70 and 10% of the electricity production. In Germany and Italy, almost 60% of the electricity is produced by non-renewable sources, with the majority of coal and natural gas, respectively. Among renewables, hydro is the dominant renewable source in Italy (16%) while in Germany wind-based electricity is the main source (21%). The corresponding carbon intensity of the Chinese electricity mix is directly taken from the GREET model. Table 1 reports the equivalent CO_2 emissions of the electricity mix of the four countries. It is important to notice that the data reported are not relative to the emission at the chimney of the power stations, but are estimated according to an LCA approach, including, for instance, plant construction and emissions related to the extraction, transport and losses of the fossil fuels. In addition, the most recent data on the share of renewables can differ from the ones assumed in this work.

The main part of a traction battery is the cell. Slurry mixtures of active materials, poly-vinylidene difluoride (PVDF) as binder, and solvents (N-methyl-2-pyrrolidone (NMP) and water) are prepared. Cathode and anode are built by coating and drying the slurry mixtures onto aluminum and copper current collectors, respectively [17]. The positive and negative electrodes are separated by polypropylene (PP) and polyethylene (PE). Cells are filled with lithium hexafluorophosphate ($LiPF_6$) salt as the electrolyte dissolved in ethylene carbonate (EC) and dimethyl carbonate (DMC). Finally, cells are grouped into modules, and modules are packed with a battery management system (BMS), a thermal management and a cooling system to form the traction battery. NMC powder, as the active cathode material, is produced via co-precipitation and calcination [47]. Graphite is the most common anode-active material while addition of silicon can be beneficial to increase the energy storage capacity [48]. Fig. 1 shows the schematic of traction battery production.

The bill of material (BOM) of LIBs can have a significant effect on the environmental impact [22]. In the literature, there are only a few BOMs available, most of them relative to NMC111 rather than NMC622 and NMC811. Some authors use Argonne's Battery Performance and Cost (BatPaC) Model [49]. The BOMs available in the literature offer lower specific energy compared to the one extracted from BatPaC. Therefore, in order to follow a conservative approach in this work, the NMC111 BOM reported by Dai et al. [12] (based on the older version of BatPaC) is taken as the reference and adjusted according to real cell data from Zu et al. [50], which is based on cells prepared in the Tianmu Lake Institute of Advanced Energy Storage Technologies. These adjusted BOMs provide lower specific energy compared to the current version of BatPaC. Table 2 reports the original BOM from Ref. [12] and the adjusted ones for NMC LIBs.

2.2. Scenario development

The available published data from the planned LIB Gigafactories is limited. Some of these facilities are commissioned based on cooperation with major Asian LIB producers [10,51]. The supply chain of needed materials remains unclear. For example, at present, NMC active cathode materials are mainly produced in China and Korea [20]. The question arises if the active cathode material (NMC powder) is produced in the emerging European LIB facilities or in East Asia, thus significantly influencing the final CO_2 emission. Therefore, this study presents three scenarios to discuss this issue.

1. In-house NMC powder. Cathode precursors are mainly produced outside of Europe. China produces 80% of global Cobalt sulfate ($CoSO_4$) [21]. Nickel is mostly refined in China, Russia, and Canada [20]. Lithium is primarily sourced from brine in Chile and Australian spodumene ores, and it has been found that using different lithium sources can result in up to 10 kg CO_2 eq./kWh difference in the GWP impact of battery production [52]. In the first scenario, these precursors are imported to Europe, and NMC powder is produced via two stages of co-precipitation and calcination within the facility. Table 3 summarizes the list of materials used in LIB, the production processes in the GREET model, and the location of production of each item for the first scenario.
2. Imported NMC powder. Another possible scenario considers NMC powder produced in Asia, specifically in China, and imported to Europe for further processes in the electrode manufacturing. This scenario may have a higher probability since the majority of European Gigafactories are joint-venture battery facilities [10]. For this scenario, the assumptions in Table 3 remain the same, except for the NMC powder production location moved to China.
3. Imported cell. Some LIB production sites are designed to increase their production capacity by using cells produced elsewhere, such as Tesla Gigafactory 1 in Nevada, USA [11,23]. This scenario considers cells produced in China to be grouped into modules and packed as a traction battery in the facility. The GWP impact of the Chinese cell is calculated according to the previous work of the authors [22], while the materials related to the battery module and pack are considered according to Table 3. These three scenarios are schematized in Fig. 2.

The production stage mainly consists of cell manufacturing, module and pack assembly. Cell manufacturing includes mixing, coating, drying, vacuum drying, and formation processes. Some of the cell production processes are executed in dry rooms, where the moisture content of the atmosphere should be less than 100 ppm [53]. The module and pack assembly shows a minimum environmental effect due to marginal energy consumption compared to cell production [8,12,14,17]. In this work, the energy consumption to produce 1 kWh of battery capacity in a Gigafactory is evaluated according to two cases reported in the literature. In case 1 (lower energy consumption), energy comes from electricity and heat (natural gas), while in case 2 (higher energy consumption) just comes from electricity due to design assumptions for a full-electric manufacturing process. The values considered in this work (29.45 and 65 kWh) represent the lower and the upper bound of energy demand, as shown in Table 4. This is confirmed by an analysis of energy consumption in the Research Factory for Battery Cells (FFB) in Germany, which showed that 41.48 kWh (20.10 of electricity, 21.28 of natural gas) are needed to produce 1 kWh battery cell capacity [25].

3. Results and discussion

3.1. Battery-grade materials

Fig. 3 shows the GWP impacts to produce 1 kg of battery-grade materials in the three European countries and China. The equivalent CO_2 values for the production of the materials in China are adopted from the previous work of the authors [22] based on a unified LCI on the GREET. Cathode active materials (NMC111, NMC622, and NMC811) production in all four countries results in relatively higher values compared to the other materials. Increasing the nickel content leads to a

Table 1
Carbon intensity of the electricity mix.

Country	[kg CO_2 eq./kWh $_{electricity}$]
Italy	0.371
France	0.085
Germany	0.409
China	0.797

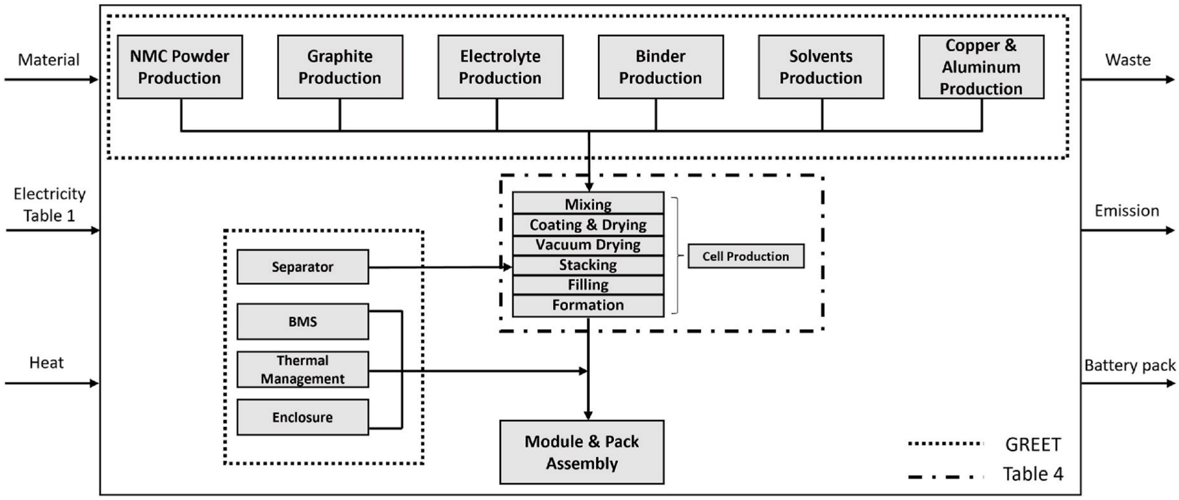

Fig. 1. Flowchart of traction battery production.

Table 2
Mass share and energy density of NMC LIBs.

Material [kg]	NMC111 [12]	NMC111	NMC622	NMC811
Cell				
NMC	41.52	38.79	35.41	32.58
Graphite	25.98	24.27	22.16	20.39
PVDF	3.55	3.32	3.03	2.79
LiPF6	2.66	2.48	2.27	2.09
EC	7.43	6.94	6.34	5.83
DMC	7.43	6.94	6.34	5.83
PE	0.42	0.39	0.36	0.33
PP	1.82	1.70	1.55	1.43
PET	0.34	0.32	0.29	0.27
Aluminum	9.80	9.15	8.36	7.69
Copper	18.84	17.60	16.07	14.78
Module and Pack				
PE	0.18	0.17	0.15	0.14
Aluminum	29.55	27.60	25.20	23.19
Copper	0.52	0.49	0.44	0.41
Steel	1.02	0.95	0.87	0.80
Glass fiber	0.80	0.75	0.68	0.63
Coolant	7.10	6.63	6.06	5.57
BMS	6.03	5.63	5.14	4.73
Total [kg]	164.99	154.13	140.73	129.47
Capacity [kWh]	23.50	23.50	23.50	23.50
Cell energy density [kWh/kg]	0.20	0.21	0.23	0.25
Pack energy density [kWh/kg]	0.142	0.152	0.167	0.182

Table 3
List of materials used in battery, the production process, and location for the first scenario.

Item	Process	Location
NMC	Production of NMC	Hosting country
Graphite	Synthetic graphite	EU
PVDF	PVDF Production	Hosting country
NMP	N-Methyl-2-pyrrolidone production	Hosting country
$LiPF_6$	Lithium hexafluorophosphate ($LiPF_6$) production	Hosting country
EC	Ethylene carbonate (EC) production	Hosting country
DMC	Dimethyl carbonate (DMC) production	Hosting country
PE	High-density polyethylene (HDPE combined)	Hosting country
PP	Mix final polypropylene	Hosting country
PET	Final PET Product: Combined	Hosting country
Aluminum	Average wrought aluminum (89% Virgin, 11% Recycled)	EU alumina reduction mix-prepared in the hosting country
Copper	Average wire and copper	15.8% Chilean, 84.2% EU mix, wire in hosting country
Steel	Average Steel	Hosting country
Glass fiber	Glass Fiber Production	Hosting country
Coolant	Engine/Powertrain coolant from ethylene glycol	Hosting country
BMS	Battery Management System Production	Hosting country

Table 4
Energy demand for cell manufacturing and module and pack assembly.

Case	Electricity [kWh/kWh]	Heat [kWh/kWh]	Capacity [GWh]	Source
1	20	9.45	30	[8]
2	65	0	35	[23]

higher GWP impact for producing 1 kg of cathode active material, more pronounced when the production happens in a country with higher carbon-intensity electricity mix. By moving from NMC111 to NMC811, GWP impact per kg of the material increases from 18.8 to 23.2 kg CO_2 eq. for production in France, where the electricity mix has the lowest CO_2 emission. The higher GWP for each kg of NMC811 compared to NMC111 is partially caused by the higher nickel content which its production is more energy-intensive than cobalt and manganese. Also, slightly higher electricity consumption during powder manufacturing and the use of lithium hydroxide (higher energy consumption in its production process), preferred for the manufacturing of NMC811 [21] (See Section 3.3), instead of lithium carbonate lead to an increase in the GWP value. Production of NMC811 in China results in a higher 30.5 kg CO_2 eq. value, 6.5 kg more than NMC111. Besides the higher shares of fossil fuel in the Chinese electricity mix, the primary data for graphite production from Engels et al. [54] and the updated production paths for PVDF, $LiPF_6$, and PE from Yin et al. [55] lead to a higher GWP impact for these materials compared to the GREET based production pathways in European countries.

The production in Europe of energy intensive materials, like aluminum and BMS, results in a significantly lower GWP. The impact of aluminum production in the three European countries is around 6 kg CO_2, regardless of the different carbon intensity of electricity grids. In fact, alumina reduction, via the Hall-Héroult process (the most electricity consumer stage of aluminum production), is obtained by using the European alumina reduction electricity mix, with an even lower carbon intensity compared to the electricity mix in France.

Fig. 4 shows the resulting GWP impact per kWh of NMC battery-

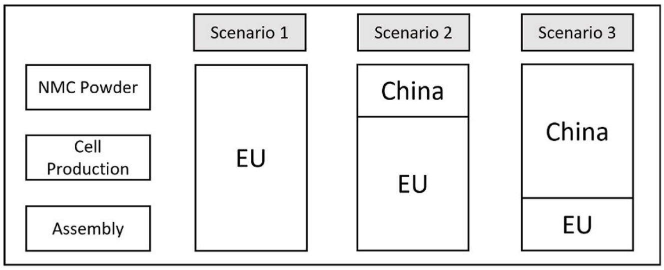

Fig. 2. Schematic of possible production scenarios for European Gigafactories.

grade materials under the first scenario assumption. In European countries, it varies between 47 and 57 kg CO_2 eq. per kWh, depending on the cathode chemistry and the location of production. These values are 30–42% lower than for production in China. Contrarily to the mass-specific analysis, increasing the nickel content results in decreasing the GWP impact due to the higher energy density of nickel-rich cathodes than for conventional NMC111. The decreasing GWP per kWh of battery-grade materials varies from 3.8 to 5.5%, with the smallest decrease where the carbon intensity of the electricity mix is lower (France). The GWP difference between NMC622 and NMC811 in all these four countries is almost negligible with a value of less than 0.8%.

NMC powder and aluminum are responsible for almost 80% of the overall GWP for NMC battery-grade materials produced in European countries, while this value decreases to 67% for production in China due to the significantly higher GWP impact of graphite and BMS. The most abundant materials in an NMC LIB are the active cathode material and aluminum (50% of LIB's total mass). In the European scenario, the mass basis GWP values of NMC powder and aluminum manufacturing are ranked first and fourth (See Fig. 3), which leads to 80% of the GWP for battery-grade material production on an energy basis. For production in France, NMC powder has a higher share in the specific cumulative GWP due to the almost constant and significant GWP impact of the precursors (upstream emissions), imported to the host countries. Other components result in significantly lower impacts due to their lower share in the BOM and their lower mass basis GWP impact.

3.2. Overall GWP impact

The energy demand for LIB production in giga-scale facilities is lower than for lab or small-scale LIB production sites. However, still, this

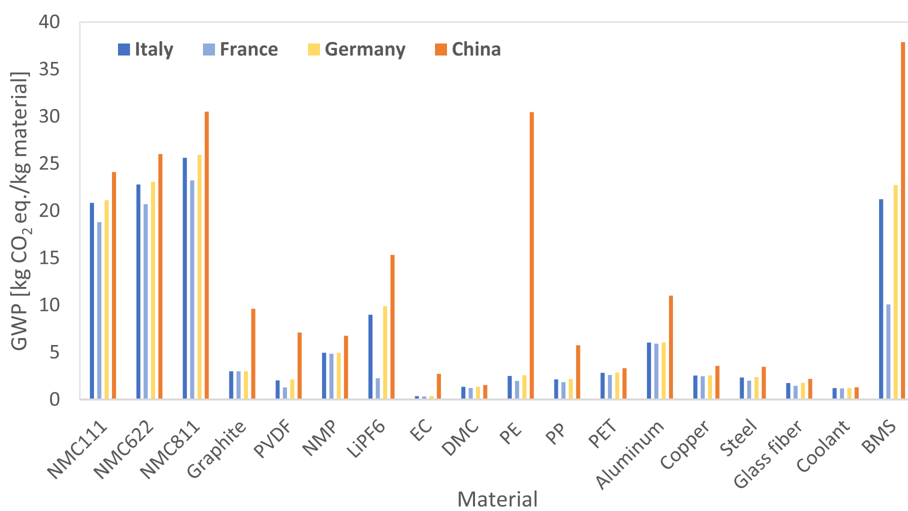

Fig. 3. The GWP impact of the production of 1 kg of battery-grade materials in different countries.

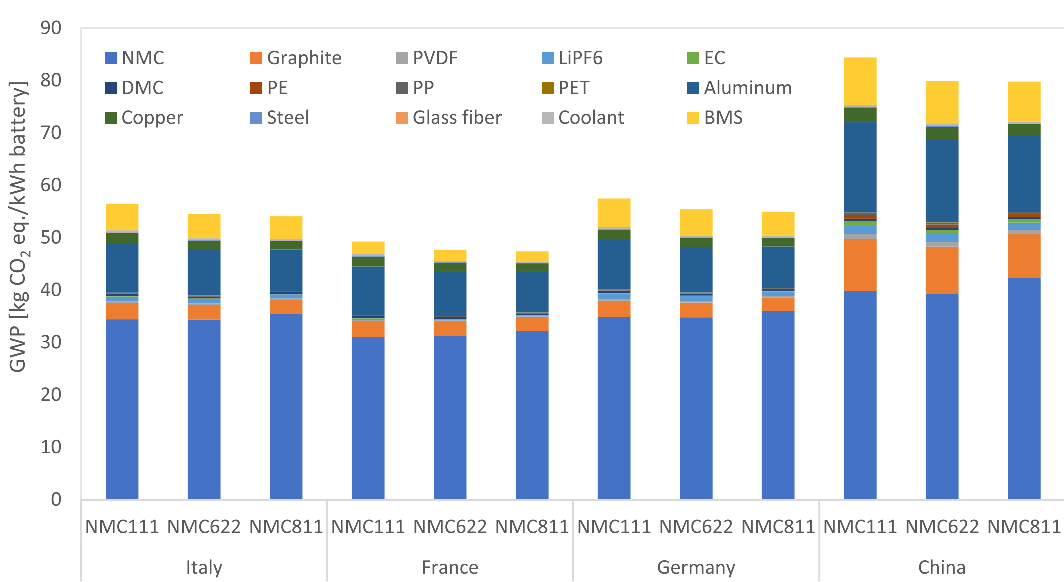

Fig. 4. The GWP impact of the production of battery-grade materials for 1 kWh capacity of different NMC LIB, based on Scenario 1.

energy demand can lead to a considerable amount of GHG emissions. Fig. 5 represents the corresponding GWP impact of manufacturing energy use defined in Section 2.2 (See Table 4) in European countries and China. Case 1 shows a lower energy demand assumption, provided by both electricity and heat, while case 2 is fully electric. For the region having the lower carbon-intensity electricity mix (France), the difference in GWP impact for both cases is negligible (almost 1 kg CO_2 eq. per kWh of LIB capacity). Electricity mixes based on fossil fuels result in a significantly higher GWP impact for fully electric LIB manufacturing facilities. The production site in China, considering the Case 2 energy consumption, generates almost 10 times more GWP impact compared to the French LIB manufacturer (51.8 vs. 5.5 kg CO_2 eq. per kWh of LIB capacity). For countries with high-carbon intensity electricity generation, using a mixture of heat and electricity can reduce the GWP impact of LIB manufacturing, assuming that each kWh of heat generated by natural gas boiler generates almost 0.3 kg CO_2 eq., less than the carbon intensity of Italian, German, and Chinese electricity mix. Utilization of a carbon burden-free heat source, such as waste heat or heat from combined heat and power plants, could furtherly reduce the GWP impact of LIB manufacturing.

According to scenarios developed in Section 2.2, the overall GWP impacts to produce 1 kWh NMC LIBs in four regions based on two manufacturing energy demand cases are plotted in Fig. 6. The GWP value can be as low as 52 kg CO_2 eq. per kWh for NMC811 production in France, or as high as 126.5 kg CO_2 eq. per kWh for German NMC111 depending on the scenario and the case. While the range for Chinese NMCs is from 99 to 136 kg CO_2 eq. per kWh. Moving the whole production to France could decrease the GHG emission up to 60% and almost 40% for LIBs manufactured in Italy or Germany. The trend of slightly decreasing GWP by increasing the nickel content is similar to the results in Section 3.1 (See Fig. 4) due to a similar manufacturing energy demand assumption for the three NMC cathode chemistries. Production of the LIB component in the European areas (scenario 1) results in considerably lower GWP impacts with respect to the third scenario (cells imported from China). Under case 2 manufacturing energy demand, the third scenario generates GWP values almost equal to the Chinese LIB production since the cell manufacturing energy consumption is significant, while the energy demand for packing is negligible [12]. The difference between the GWP of the first and third scenarios can be from 36 to 127% for NMC111 produced in Germany (case 1) and NMC811 (case 2) produced in France, respectively. However, still importing cells and producing LIBs in these three European countries can decrease the GWP impact by between 6 and 12% depending on the country and cathode chemistry. The second scenario (importing the NMC powder) can be a promising option. The increase in GWP value with respect to the first scenario is in the range of 6–19%, the higher value associated with LIB production in France.

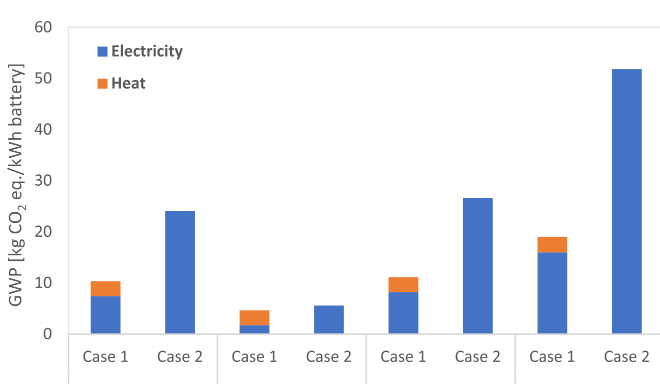

Fig. 5. The GWP impact of LIB manufacturing energy demand per kWh of battery capacity.

3.3. Sensitivity analysis of the lithium compound source

In previous sections, we considered a mixed source for lithium compound, according to the GREET model: lithium carbonate (Li_2CO_3) used for NMC111 and NMC622 is 45% from Chilean brine-based lithium and 55% from ore, while NMC811 makes use of lithium hydroxide (LiOH), 80% sourced from ore.

In this section, we compare the GWP impact of three different lithium compound sources, under the first scenario of Section 2.2. Namely:

- Brine-based lithium ('Brine' in Fig. 7): LiOH is produced from Li_2CO_3 available from brines
- Ore-based lithium ('Ore' in Fig. 7): LiOH and Li_2CO_3 directly produced from spodumene ore
- A mixed source as mentioned above ('Mixed' in Fig. 7)

Fig. 7 shows that the GWP impact is lower for brines, rather than for spodumene ores, in all four regions. The decrease is higher for NMC111 and NMC622, 11 and 10 kg CO_2 eq. per kWh, respectively, compared to NMC811, around 5 kg CO_2 eq. per kWh. This GWP reduction can be explained by the fact that obtaining the lithium compound, LiOH and Li_2CO_3, from brine is less energy intensive compared to ore-based lithium which leads to lower GWP impacts. In other words, the energy consumption during the mining, the concentration stages of spodumene, and the production of lithium compounds from concentrated spodumene is higher than the brine-based pathway [56]. Utilizing the brine-based lithium in European Gigafactories can be an opportunity to further reduce the GWP impact of LIB production. Contrary to the results obtained in Sections 3.1 and 3.2, brine-based lithium brings about a slightly lower GWP impact for NMC622 compared to NMC811 (for instance, 46.7 kg CO_2eq. per kWh vs. 47.9 for production in France under case 1 energy consumption). This can be explained by the larger benefit of using brine-based lithium in decreasing the GWP value of NMC622 compared to NMC811. Since the brine-sourced lithium hydroxide used for NMC811 needs an extra energy consumption for the indirect production process from lithium carbonate, while the lithium carbonate used in NMC622 can be obtained directly from brines.

3.4. Effect of regional LIB production on BEV's carbon footprint

BEVs are free of tailpipe emissions, while their production process, specifically the LIB production, and the electricity mix used for battery charging brings about significant CO_2 emissions [4]. This section shows a simplified analysis of the GWP impact of the utilization phase of two vehicle categories: a small city car, equipped with a 42 kWh gross capacity LIB, and a compact executive BEV with an 83.9 kWh LIB [57,58]. The technical specifications of these BEVs and their internal combustion engine (ICE) versions [59,60] considering the combined real consumptions (including the charging losses) are summarized in Table 5.

We assumed that the battery pack is manufactured in the same country where the BEV is circulating. In order to provide a broader comparison of the effect of LIB production scenarios, the LIB is produced under the first scenario and case 1 manufacturing energy demand (S.1-C.1, lower impact) or the third scenario and case 2 (S.3-C.2, higher impact) (See Fig. 6). The third scenario can be seen as an equivalent to the Chinese LIB; therefore, the results of this scenario are comparable to the vehicles which are equipped with a LIB imported from China. The NMC622 is selected for this case study due to its frequent implementation in recent BEVs [8]. The analysis focuses on the effect of the LIB production place, scenarios, the used electricity grid for recharging the battery, and the distance covered by the vehicle: the GWP impact of vehicle production (excluding LIB) is neglected, or better considered equal to a comparable car with an ICE. The BEV carbon footprint under different scenarios is compared with three thresholds:

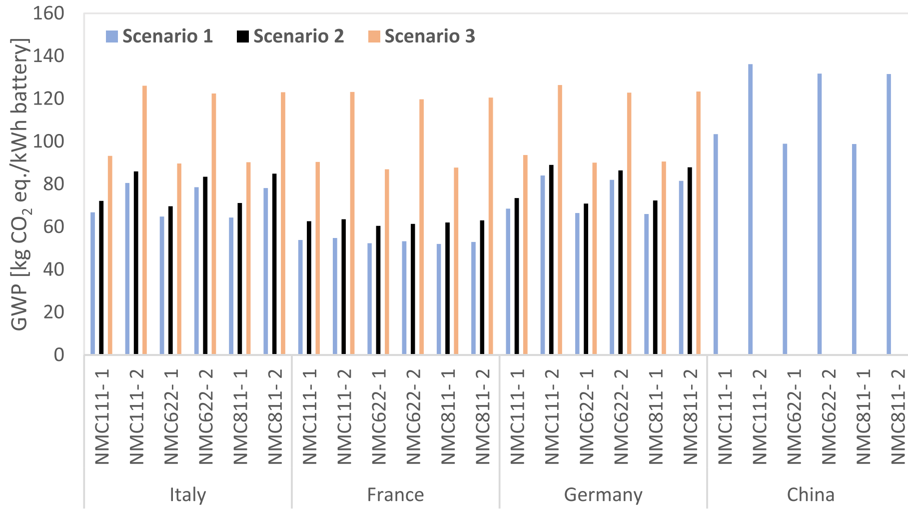

Fig. 6. The GWP impacts of the production of 1 kWh of battery capacity based on the three scenarios.
Cases 1 and 2 are representative of manufacturing energy demand of Table 4.

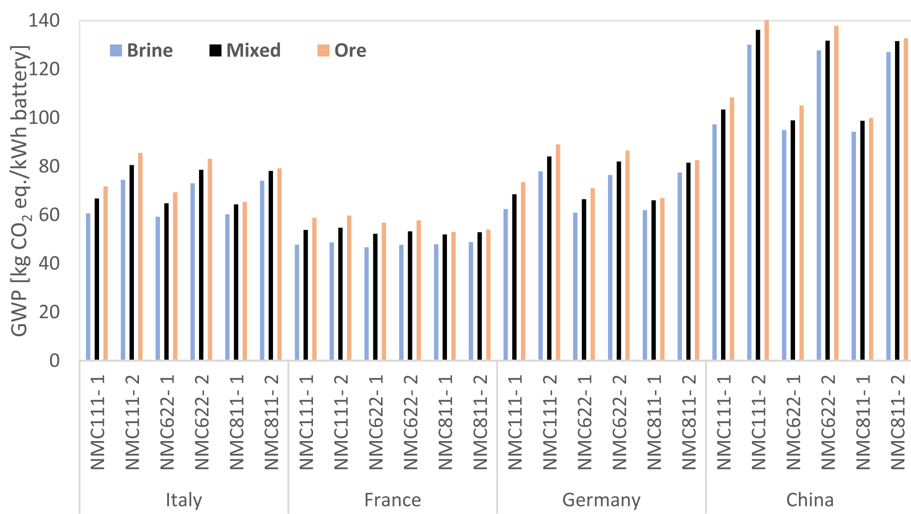

Fig. 7. The GWP impacts of the production of 1 kWh battery capacity based on the first scenario and lithium compound sources, 1 and 2 are representative of manufacturing energy demand in case 1 and case 2.

Table 5
Vehicles specifications.

Vehicle Name	BEV		ICE	
	LIB capacity [kWh]	Consumption [kWh/100 km]	Consumption [l/100 km]	WTW [g CO_2/km]
Small city car	42	17.4	5.5	152
Compact executive car	83.9	19.5	6.8	187

- The well-to-wheel (WTW) emission of the ICE version of the vehicle
- The ICE average tailpipe emission regulation proposed by the European Parliament (95 g CO_2 eq./km) [61], which is defined as Regulation-EU.
- The EU regulation plus the upstream impact of the fuel, named Regulation-EU-WTW. The value for the upstream impact is extracted from Eriksson and Ahlgren [62].

According to EU regulations, the carbon intensities of the electricity mixes should be reduced over the upcoming years by increasing the share of renewable electricity and phasing out the coal power plants [63,64]. For 2030, the indicative intensity level that would be consistent with the EU's climate targets is in a range of 110–118 g CO_2 eq./kWh $_{electricity}$ [65]. Therefore, considering a more conservative approach, the regional electricity mix carbon intensities for Italy and Germany, reported in Table 1, are reduced on a yearly basis to reach around 118 g CO_2 eq./kWh $_{electricity}$ over a ten-year period (France's electricity mix, already, has a lower carbon intensity than 100 g CO_2 eq./kWh $_{electricity}$.). In order to include the transmission and distribution losses (T & D losses) within the grid, the BEV's consumption values are increased by a factor of 6%. The 6% value is almost the average of T & D losses of the three countries under investigation [66]. Fig. 8 plots the hypothetical trend of decreasing carbon emissions of these two European countries. Firstly, as the baseline, we assumed that the vehicle covers 20,000 km each year, a vehicle lifetime of 200,000 km is a common value in the literature [67–70]. Later, the distance covered is considered based on the average annual distance coverage for each country (reported in Table 6) to indicate a more realistic driving condition.

Figs. 9A and B show the carbon footprint of the small city and

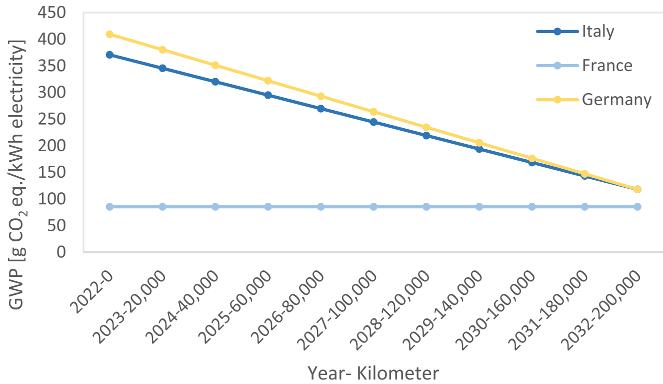

Fig. 8. Regional electricity carbon intensity over a ten-year period.

compact executive BEVs for distances covered from 20,000 to 200,000 km (20,000 km/year), respectively. The small BEV circulating in France equipped with a LIB produced in France under the lower impact condition (light blue solid line) reaches an equivalent CO_2 emission equal to 95 g per km (Regulation-EU) after almost 32,000 km distance covered. Utilizing an assembled LIB (cell manufactured in China under the higher impact condition) in the BEV charged under the French electricity mix (light blue dashed line) postpones this cross point to slightly after 64,000 km. Considering the EU regulation plus the upstream impact of gasoline, depending on the production scenario, the small BEV reaches this emission level slightly after 24,000 and 52,000 km. When this BEV is compared directly with its ICE version, the CO_2 mitigation effect occurs around 15,000 (not shown here) and 40,000 km for in-house and assembled LIB, respectively. BEVs circulating in Italy and Germany show an almost similar carbon footprint, slightly lower for Italy, and they reach EU regulation in almost 72,000 and 80,000 km, respectively. Due to the vicinity of their electricity carbon intensity, when the in-house LIB is substituted with the assembled version, the carbon footprint behavior becomes more similar for Italy and Germany. Both BEVs reach the EU regulation on CO_2 emission of passenger cars within 110,000 to 115,000 km distance covered. Under all conditions, the small BEV reaches a smaller carbon footprint compared to the ICE version of the vehicle after a 60,000 km distance covered.

The LIB capacity of the compact executive BEV is double the one in the small BEV, therefore, as it is shown in Fig. 9B, the cross points with respect to the three thresholds are shifted toward longer travel distances, mainly, due to a higher CO_2 burden of the larger LIB. The compact executive BEV circulating in France reaches 95 g CO_2 eq. per km after 60,000 and 130,000 km for the in-house and assembled LIBs, respectively. These values for both Italy and Germany are almost 125,000 and 180,000 km. The lower carbon emission of this BEV compared to its ICE version can be obtained at around 30,000 and 50,000 km traveled distance in France and Italy or Germany for the in-house LIB, respectively. In the case of assembled LIB, these values are 60,000 and 80,000 km. Comparing Figs. 9A and B, regardless of the LIB production scenario and the BEV circulating location, the small and compact executive BEVs result in lower CO_2 emission than their ICE versions after 3 and 4 years (60,000 and 80,000 km), respectively. This statement indicates that, in terms of the CO_2 mitigation effect, small city BEVs outperform the ICE version of the vehicle earlier with respect to larger BEVs and their ICV equivalents. Considering France as the representative of a location with low carbon-intensity electricity, the small and compact executive BEVs equipped with lower impactful LIB become less CO_2 pollutant within less than a year and a year and a half (15,000 and 30,000 km) compared to their ICE versions. As an example, Fig. 9B also shows the CO_2 emission of the compact executive BEV equipped with the assembled LIB circulating in Italy recharged under the current Italian electricity mix (371 g CO_2 eq./kWh $_{electricity}$) over the life cycle. It can be seen that this BEV in Italy recharged with the current electricity mix does not even reach the EU regulation plus the upstream impact during its life cycle while the same BEV reaches well below the EU regulation level under the decreasing electricity carbon intensity assumption. These results emphasize the effect of the carbon intensity of the electricity mix and confirm that the benefits of electric mobility are maximized by the decarbonization of electricity grids in the upcoming years. Also, it suggests that the priority of the substitution of ICE vehicles with BEVs should be for the smaller vehicles within the countries with lower impactful electricity grids.

Figs. 10A and B are plotted based on the same data of Figs. 9A and B except for the 20,000 km yearly distance coverage which is replaced with the average annual distance coverage for each country (See Table 6). For the sake of simplicity, the Regulation-EU and Regulation-EU-WTW lines are not considered in these two plots. Comparing these two series of plots shows that for both vehicles the CO_2 mitigation effect occurs at least half a year later with respect to the baseline 20,000 km annual coverage. For example, in France, the small BEV equipped with French LIB reaches below its ICE version CO_2 emission level a year later if the French average annual distance is considered (0.5 years vs. 1.5 years). For the BEV with the larger or the assembled LIB, or for the locations with higher electricity carbon intensity the gap is even larger due to the higher impact regarding the battery. For instance, from Fig. 10B, the compact executive BEV equipped with the assembled LIB circulating in Italy becomes less CO_2 emitter compared to its ICE version after 7 years while under the 20,000 km yearly distance coverage after 4 years. Contrary to Figs. 9A and B, despite the higher carbon intensity of the German electricity mix and slightly higher impact of the LIBs produced or assembled in Germany, BEVs in Germany cross the WTW emission of the ICE versions earlier (in terms of time) compared to Italy due to the higher annual traveled distances in Germany. Also, it can be noted that the CO_2 emission levels of these BEVs traveling according to the average annual distance are higher after the ten-year life cycle compared to the baseline 20,000 km/year. Comparing the two series of Figs. 9 and 10 suggest that the countries which have a higher average annual distance coverage benefit more from electric mobility. Another point that can be understood from these two series of figures is the large initial difference in the carbon footprint of ICEVs and BEVs, which indicates that by substituting the ICEVs with BEVs a higher CO_2 emission will be introduced into the environment due to the addition of LIBs to the vehicles, and only with mileage may this increase be compensated for [22].

The overall result shows that life cycle emissions will not be zero even with European battery production chains. Assuming a scenario with more likelihood, not all the items could be produced in the EU which would increase the global GHG emissions. However, over the upcoming years, by reduction of the electricity carbon intensity, the emission of LIB production could be further decreased. Recalling the fact that in this work, countries with relatively low-emission electricity in the EU landscape have been considered. In the case of a location like Poland, which currently hosts the largest European LIB production capacity and has an almost coal-based electricity production, the life cycle emission of both production of LIB and the electric mobility is higher. The emissions can be compared to the Chinese LIB manufacturing and BEV utilization scenario which is considerably higher than the target average emission of new ICE passenger cars [22]. Therefore, it is necessary to evaluate alternatives to BEVs by considering life cycle emissions. It can be emphasized that the percentages of biofuels in current fuels (which would have decreased CO_2 emissions from the ICEVs that were compared) were neglected. In addition, it can be

Table 6
Average annual distance coverage for each vehicle [71].

Country	Average Distance [km/year]
Italy	10,712
France	11,924
Germany	13,602

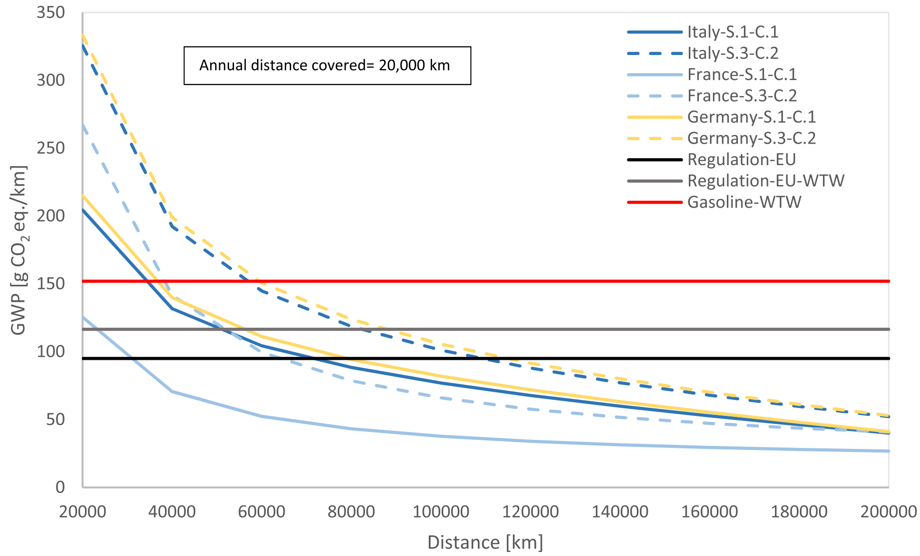

Fig. 9A. The GWP impact of the use phase of a small BEV per km circulating 200,000 km in Italy, France, and Germany, equipped with LIB produced in the same country under Scenario 1-Case 1 (labeled with S.1-C.1, solid lines) or Scenario3-Case2 (labeled with S.3-C.2, dashed lines) compared to ICE average emission in Europe [61] (black line), and EU regulation plus the upstream impact of the fuel (gray line), and the similar ICE version of the vehicle (red line) [59].

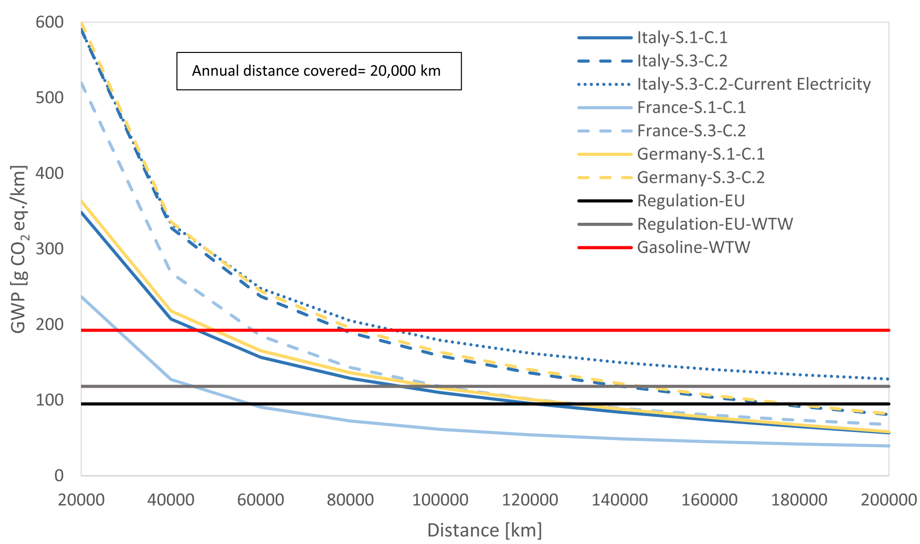

Fig. 9B. The GWP impact of the use phase of a compact executive BEV per km circulating 200,000 km in Italy, France, and Germany, equipped with LIB produced in the same country under Scenario 1-Case 1 (labeled with S.1-C.1, solid lines) or Scenario3-Case2 (labeled with S.3-C.2, dashed lines) compared to ICE average emission in Europe [61] (black line), EU regulation plus the upstream impact of the fuel (gray line), and the similar ICE version of the vehicle (red line) [60]

pointed out that there are commercially available vehicles equipped with an ICE with lower emissions than the vehicles considered here, however, we have not considered them since there is no electric version of the same car.

4. Conclusion

The GWP impact of NMC battery production in Germany, France, and Italy was studied. According to the planned Giga-scale LIB factories in Europe, these three countries become the largest LIB producers in Europe by 2030. A cradle-to-gate LCA was performed within the open-access GREET model considering three different production scenarios to assess possible supply chains. Two bounds for manufacturing energy demand were assumed to show the possible variations in the overall GWP impact of LIB production in Giga factories. Also, the GWP impacts of NMC111, NMC622, and emerging NMC8111 cathode chemistries for different lithium sources were compared. Finally, a simplified analysis evaluated the effect of regional LIB production on BEVs' carbon footprint.

Moving the whole production phase, including the NMC powder production based on the imported precursors, to European countries with lower electricity carbon intensity can significantly reduce the GWP impact associated with LIBs' production and secure the energy storage supply chain for European countries. The overall GWP for the production of 1 kWh of NMC battery storage in European Giga factories can vary from 46.5 to 126.5 kg CO_2 eq., regarding the level of domestic production, region of production, manufacturing energy consumption, and the lithium source. For scenarios 1 and 2, in which the production of precursors and the NMC powder, respectively, occurs overseas, the reduction in GWP impact compared to the Chinese LIB is significant. The decrease is in the range of 26–53% for the second scenario and it boosts to 32 and 60% in the first scenario. Among the three countries, France shows the lowest GWP impact. Italy and Germany are ranked second and third, respectively. Production under the third scenario is still beneficial

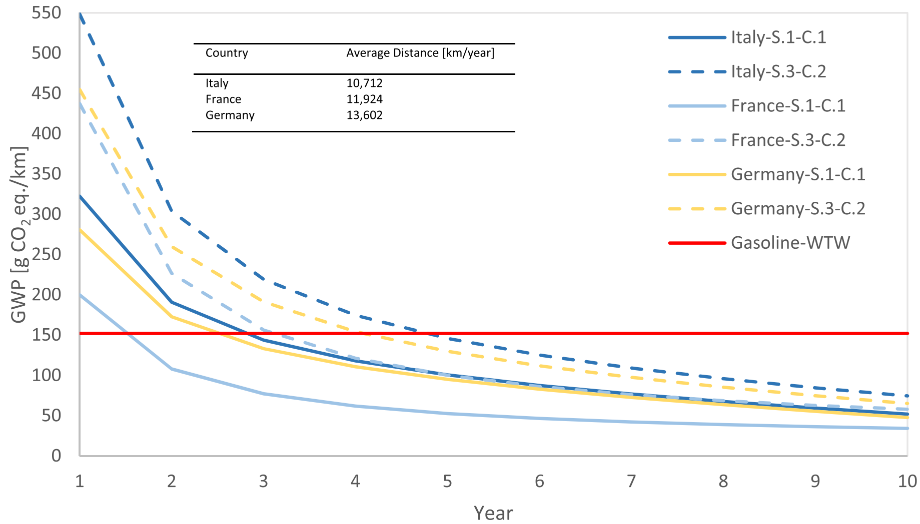

Fig. 10A. The GWP impact of the use phase of a small BEV per km based on the average annual distance circulating in Italy, France, and Germany, equipped with LIB produced in the same country under Scenario 1- Case 1 (labeled with S.1-C.1, solid lines) or Scenario 3- Case 2 (labeled with S.3-C.2, dashed lines) compared to the similar ICE version of the vehicle (red line) [59].

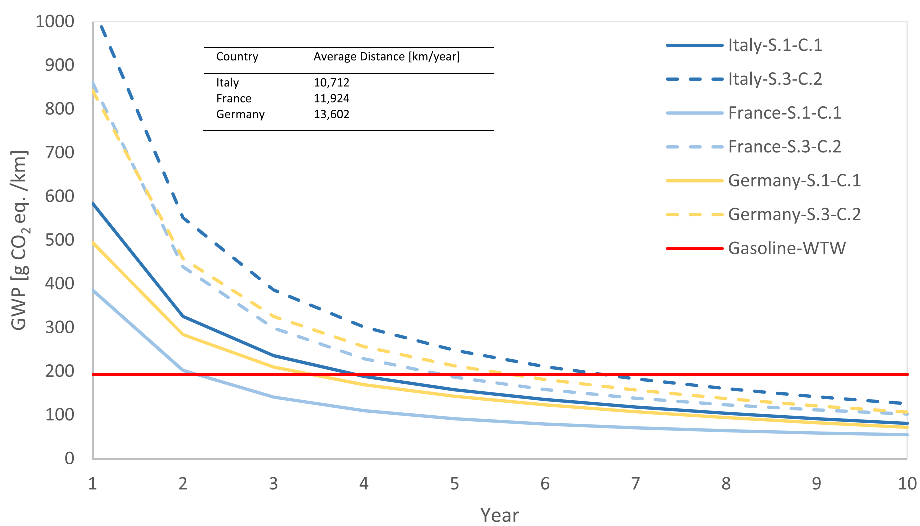

Fig. 10B. The GWP impact of the use phase of a compact executive BEV per km based on the average annual distance circulating in Italy, France, and Germany, equipped with LIB produced in the same country under Scenario 1- Case 1 (labeled with S.1-C.1, solid lines) or Scenario 3- Case 2 (labeled with S.3-C.2, dashed lines) compared to the similar ICE version of the vehicle (red line) [60]

in the sense of GWP reduction, however, this reduction is minimized (6–12%). The GWP impact decreases by increasing the active cathode nickel content for mixed and ore-sourced lithium compounds. While the lithium is supplied from Chilean brines, NMC622 outperforms NMC811 in GWP impact.

Moreover, the application of domestic and assembled NMC622 through a simplified analysis of the use phase of two different classes of BEVs circulating in the three European countries was studied. The useful life for BEVs was considered equal to ten years. An optimistic progressive decrease in emissions associated with electricity production in accordance with EU targets was considered in the analysis. Based on average driving distances of 20,000 km per year and the average annual use of cars in different countries, it takes about 30,000–80,000 km to have the same emissions as cars powered entirely by fossil fuels. On the one hand, the overall result shows that life cycle emissions will not be zero even with European battery production chains. On the other hand, the analysis shows the opportunity for further CO_2 mitigation effect of electric mobility utilizing the European in-house built LIBs. This benefit is maximized for regions with grids with lower carbon intensity, higher average annual distance coverage, and smaller BEVs.

The need for further real-world data, actual supply chain, and LCA studies to obtain a reliable impact assessment of the Giga-scale LIB production facilities is evident. Within the next years, some of these European Giga factories will start mass production, which enables the possibility to acquire the necessary data to evaluate the actual impacts and in case, revise the policies on mobility, i.e., to further promote electric mobility.

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.

Data availability

Data will be made available on request.

References

[1] Nimesh V, Kumari R, Soni N, Goswami AK, Mahendra Reddy V. Implication viability assessment of electric vehicles for different regions: an approach of life cycle assessment considering exergy analysis and battery degradation. Energy Convers Manag 2021;237:114104. https://doi.org/10.1016/J.ENCONMAN.2021.114104.

[2] Global EV outlook. International Energy Agency (IEA); 2021. https://www.iea.org/reports/global-ev-outlook-2021. [Accessed 19 June 2022].

[3] Department for Transport. COP26 declaration on accelerating the transition to 100% zero emission cars and vans 2021. https://www.gov.uk/government/publications/cop26-declaration-zero-emission-cars-and-vans/cop26-declaration-on-accelerating-the-transition-to-100-zero-emission-cars-and-vans(accessed June 19, 2022)..

[4] Sacchi R, Bauer C, Cox B, Mutel C. When, where and how can the electrification of passenger cars reduce greenhouse gas emissions? Renew Sustain Energy Rev 2022; 162:112475. https://doi.org/10.1016/J.RSER.2022.112475.

[5] Rahman MM, Oni AO, Gemechu E, Kumar A. Assessment of energy storage technologies: a review. Energy Convers Manag 2020;223:113295. https://doi.org/10.1016/J.ENCONMAN.2020.113295.

[6] Peters JF, Baumann M, Zimmermann B, Braun J, Weil M. The environmental impact of Li-Ion batteries and the role of key parameters – a review. Renew Sustain Energy Rev 2017;67:491–506. https://doi.org/10.1016/J.RSER.2016.08.039.

[7] Yonhap News Agency. LG Energy Solution ranks second in EV battery market in Jan.-Nov. period 2020. https://en.yna.co.kr/view/AEN20201231001000320. [Accessed 20 June 2022].

[8] Sun X, Luo X, Zhang Z, Meng F, Yang J. Life cycle assessment of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles. J Clean Prod 2020;273:123006. https://doi.org/10.1016/J.JCLEPRO.2020.123006.

[9] M. S. Alice Yu. Top electric vehicle markets dominate lithium-ion battery capacity growth 2021. https://www.spglobal.com/marketintelligence/en/news-insights/blog/top-electric-vehicle-markets-dominate-lithium-ion-battery-capacity-growth (accessed June 20, 2022).

[10] Moores S. The global battery arms race: lithium-ion battery gigafactories and their supply chain. Oxford Energy Forum; 2021. p. 26–30.

[11] Tesla. Planned 2020 gigafactory production exceeds 2013 global production 2014. https://www.tesla.com/sites/default/files/blog_attachments/gigafactory.pdf.

[12] Dai Q, Kelly JC, Gaines L, Wang M. Life cycle analysis of lithium-ion batteries for automotive applications. https://doi.org/10.3390/batteries5020048; 2019.

[13] Majeau-Bettez G, Hawkins TR, Hammer Strømman A. Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. Environ Sci Technol 2011;45:4548–54. https://doi.org/10.1021/es103607c.

[14] Ager-Wick Ellingsen L, Majeau-Bettez G, Singh B, Kumar Srivastava A, Ole Valøen L. Hammer strømman A. R E S E A R C H A N D A N A ly S I S. Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack 2013. https://doi.org/10.1111/jiec.12072.

[15] Weidema Bo. Ecoinvent V.2.2. 2010. https://ecoinvent.org/wp-content/uploads/2020/08/201004_report_of_changes_ecoinvent_2.1_to_2.2_compressed.pdf. [Accessed 5 July 2022].

[16] Chordia M, Nordelöf A, Linda, Ellingsen A-W. Environmental life cycle implications of upscaling lithium-ion battery production. Int J Life Cycle Assess 2021. https://doi.org/10.1007/s11367-021-01976-0.

[17] Kim HC, Wallington TJ, Arsenault R, Bae C, Ahn S, Lee J. Cradle-to-Gate emissions from a commercial electric vehicle Li-ion battery: a comparative analysis. https://doi.org/10.1021/acs.est.6b00830; 2016.

[18] Erakca M, Pinto Bautista S, Moghaddas S, Baumann M, Bauer W, Leuthner L, et al. Closing gaps in LCA of lithium-ion batteries: LCA of lab-scale cell production with new primary data. J Clean Prod 2023;384:135510. https://doi.org/10.1016/j.jclepro.2022.135510.

[19] Argonne National Laboratory. GREET model: The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model n.d https://greet.es.anl.gov/(accessed July 5, 2022)..

[20] Kelly JC, Dai Q, Wang M, Gov J. Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries Mitigation and Adaptation Strategies for Global Change 2020;25. https://doi.org/10.1007/s11027-019-09869-2. 371-396 2020.

[21] Winjobi O, Kelly JC, Dai Q. Life-cycle analysis, by global region, of automotive lithium-ion nickel manganese cobalt batteries of varying nickel content. Sustainable Materials and Technologies 2022;32:e00415. https://doi.org/10.1016/J.SUSMAT.2022.E00415.

[22] Bonalumi D, Kolahchian Tabrizi M. Re-Evaluation of the global warming potential for the production of lithium-ion batteries with nickel–manganese–cobalt cathode chemistries in China. Energy Fuels 2022;36:13753–67. https://doi.org/10.1021/acs.energyfuels.2c02204.

[23] Davidsson Kurland S. Energy use for GWh-scale lithium-ion battery production. Environ Res Commun 2020;2:12001. https://doi.org/10.1088/2515-7620/ab5e1e.

[24] Jinasena A, Stokke Burheim O, Hammer Strømman A. A Flexible Model for Benchmarking the Energy Usage of Automotive Lithium-Ion Battery Cell Manufacturing 2021 https://doi.org/10.3390/batteries..

[25] Degen F, Schütte M. Life cycle assessment of the energy consumption and GHG emissions of state-of-the-art automotive battery cell production. J Clean Prod 2022; 330:129798. https://doi.org/10.1016/J.JCLEPRO.2021.129798.

[26] Li M, Zhang X, Li G. A comparative assessment of battery and fuel cell electric vehicles using a well-to-wheel analysis. Energy 2016;94:693–704. https://doi.org/10.1016/j.energy.2015.11.023.

[27] Patil V, Shastry V, Himabindu M, Ravikrishna RV. Life-cycle analysis of energy and greenhouse gas emissions of automotive fuels in India: Part 2 – well-to-wheels analysis. Energy 2016;96:699–712. https://doi.org/10.1016/j.energy.2015.11.076.

[28] Sharma A, Strezov V. Life cycle environmental and economic impact assessment of alternative transport fuels and power-train technologies. Energy 2017;133: 1132–41. https://doi.org/10.1016/j.energy.2017.04.160.

[29] Qiao Q, Zhao F, Liu Z, He X, Hao H. Life cycle greenhouse gas emissions of Electric Vehicles in China: combining the vehicle cycle and fuel cycle. Energy 2019;177: 222–33. https://doi.org/10.1016/j.energy.2019.04.080.

[30] Xiong S, Wang Y, Bai B, Ma X. A hybrid life cycle assessment of the large-scale application of electric vehicles. Energy 2021;216:119314. https://doi.org/10.1016/j.energy.2020.119314.

[31] García A, Monsalve-Serrano J, Martinez-Boggio S, Soria Alcaide R. Carbon footprint of battery electric vehicles considering average and marginal electricity mix. Energy 2023;268:126691. https://doi.org/10.1016/j.energy.2023.126691.

[32] Desreveaux A, Bouscayrol A, Trigui R, Hittinger E, Castex E, Sirbu GM. Accurate energy consumption for comparison of climate change impact of thermal and electric vehicles. Energy 2023;268:126637. https://doi.org/10.1016/j.energy.2023.126637.

[33] Fusco Rovai F, Regina da Cal Seixas S, Keutenedjian Mady CE. Regional energy policies for electrifying car fleets. Energy 2023;278:127908. https://doi.org/10.1016/j.energy.2023.127908.

[34] Peng T, Ren L, Ou X. Development and application of life-cycle energy consumption and carbon footprint analysis model for passenger vehicles in China. Energy 2023;282:128412. https://doi.org/10.1016/j.energy.2023.128412.

[35] Marija Maisch. Europe's gigafactory boom in full swing with another plant announcement 2022.

[36] International Organization for Standardization. ISO 14040:2006,Environmental management — Life cycle assessment — Principles and framework 2006 https://www.iso.org/standard/37456.html (accessed July 5, 2022)..

[37] International Organization for Standardization. ISO 14044:2006,Environmental management — life cycle assessment — requirements and guidelines. https://www.iso.org/standard/38498.html. [Accessed 5 July 2022].

[38] Nitta N, Wu F, Lee JT, Yushin G. Li-ion battery materials: present and future. Mater Today 2015;18:252–64. https://doi.org/10.1016/J.MATTOD.2014.10.040.

[39] Ding Y, Cano ZP, Yu A, Lu J, Zhongwei Chen ·. Automotive Li-ion batteries. Current Status and Future Perspectives 2019;2:1–28. https://doi.org/10.1007/s41918-018-0022-z.

[40] Ma Q, Zeng X-X, Yue J, Yin Y-X, Zuo T-T, Liang J-Y, et al. CommuniCation 1803854 (1 of 7) viscoelastic and nonflammable interface design-enabled dendrite-free and safe solid lithium metal batteries. Adv Energy Mater 2019;9:1803854. https://doi.org/10.1002/aenm.201803854.

[41] Murdock BE, Toghill KE, Tapia-Ruiz N, Murdock BE, Toghill KE, Tapia-Ruiz N. A Perspective on the Sustainability of Cathode Materials used in Lithium-Ion Batteries 2021 https://doi.org/10.1002/aenm.202102028..

[42] Accardo A, Dotelli G, Musa ML, Spessa E. Life cycle assessment of an NMC battery for application to electric light-duty commercial vehicles and comparison with a sodium-nickel-chloride battery. Appl Sci 2021;2021:1160. https://doi.org/10.3390/app11031160.

[43] IRENA. Energy profile, Germany. https://www.irena.org/IRENADocuments/Statistical_Profiles/Europe/Germany_Europe_RE_SP.pdf. [Accessed 4 July 2022].

[44] IRENA. Energy profile, France. https://www.irena.org/IRENADocuments/Statistical_Profiles/Europe/France_Europe_RE_SP.pdf. [Accessed 4 July 2022].

[45] IRENA. Energy profile, Italy. https://www.irena.org/IRENADocuments/Statistical_Profiles/Europe/Italy_Europe_RE_SP.pdf. [Accessed 4 July 2022].

[46] Scarlat N, Prussi M, Padella M. Quantification of the carbon intensity of electricity produced and used in Europe. Appl Energy 2022;305:117901. https://doi.org/10.1016/J.APENERGY.2021.117901.

[47] Ahmed S, Nelson PA, Gallagher KG, Susarla N, Dees DW. Cost and energy demand of producing nickel manganese cobalt cathode material for lithium ion batteries. J Power Sources 2017;342:733–40. https://doi.org/10.1016/J.JPOWSOUR.2016.12.069.

[48] Kallitsis E, Korre A, Kelsall G, Kupfersberger M, Nie Z. Environmental life cycle assessment of the production in China of lithium-ion batteries with nickel-cobalt-manganese cathodes utilising novel electrode chemistries. J Clean Prod 2020;254: 120067. https://doi.org/10.1016/J.JCLEPRO.2020.120067.

[49] Argonne National Laboratory. BatPaC: a lithium-ion battery performance and cost model for electric-drive vehicles. https://www.anl.gov/cse/batpac-model-software. [Accessed 6 July 2022].

[50] Zu C, Ren Y, Guo F, Yu H, Li H. A reflection on lithium-ion batteries from a lithium-resource perspective. https://doi.org/10.1002/aesr.202100062; 2021.

[51] Cooke P. Gigafactory logistics in space and time: tesla's fourth gigafactory and its rivals. Sustainability 2020;12:2044. https://doi.org/10.3390/su12052044.

[52] Kelly JC, Wang M, Dai Q, Winjobi O. Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries. Resour Conserv Recycl 2021;174:105762. https://doi.org/10.1016/J.RESCONREC.2021.105762.

[53] Ahmed S, Nelson PA, Gallagher KG, Dees DW. Energy impact of cathode drying and solvent recovery during lithium-ion battery manufacturing. J Power Sources 2016; 322:169–78. https://doi.org/10.1016/J.JPOWSOUR.2016.04.102.

[54] Engels P, Cerdas F, Dettmer T, Frey C, Hentschel J, Herrmann C, et al. Life cycle assessment of natural graphite production for lithium-ion battery anodes based on industrial primary data. J Clean Prod 2022;336:130474. https://doi.org/10.1016/J.JCLEPRO.2022.130474.

[55] Yin R, Hu S, Yang Y. Life cycle inventories of the commonly used materials for lithium-ion batteries in China. J Clean Prod 2019;227:960–71. https://doi.org/10.1016/J.JCLEPRO.2019.04.186.
[56] Kelly JC, Wang M, Dai Q, Winjobi O. Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries. Resour Conserv Recycl 2021;174:105762. https://doi.org/10.1016/J.RESCONREC.2021.105762.
[57] Allgemeiner Deutscher Automobil-Club (ADAC). Fiat 500e (42 kWh) Cabrio Icon. https://www.adac.de/rund-ums-fahrzeug/autokatalog/marken-modelle/fiat/fiat-500-elektro/. [Accessed 13 July 2022].
[58] Allgemeiner Deutscher Automobil-Club (ADAC). BMW i4 eDrive40 2022 https://www.adac.de/rund-ums-fahrzeug/autokatalog/marken-modelle/bmw/i4/i04/320896/#eco-test (accessed December 20, 2022)..
[59] Allgemeiner Deutscher Automobil-Club (ADAC). Fiat 500 0.9 8V TwinAir Turbo Start&Stopp Lounge 2016 https://www.adac.de/rund-ums-fahrzeug/autokatalog/marken-modelle/fiat/500/312-facelift/249142/#eco-test (accessed July 13, 2022)..
[60] Allgemeiner Deutscher Automobil-Club (ADAC). BMW 430i Gran Coupé Steptronic 2022 https://www.adac.de/rund-ums-fahrzeug/autokatalog/marken-modelle/bmw/4er-reihe/g22-g23-g26-g82-g83/320916/#eco-test (accessed December 20, 2022)..
[61] The European parliament and the council of the European Union Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles, (EC) No 443/2009 and (EU) No 510/2011. 2019, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R0631. [Accessed 12 July 2022].
[62] Eriksson M, Ahlgren S. LCAs of petrol and diesel: a literature review. Rapport: Institutionen För Energi Och Teknik, SLU); 2013.
[63] European Council. Infographic - fit for 55: how the EU plans to boost renewable energy 2022. European Council Council of the European Union (accessed December 10, 2022).
[64] European Commission. Coal regions in transition 2022 https://energy.ec.europa.eu/topics/oil-gas-and-coal/eu-coal-regions/coal-regions-transition_en (accessed December 10, 2022)..
[65] European Environment Agency. Greenhouse gas emission intensity of electricity generation in Europe 2022 https://www.eea.europa.eu/ims/greenhouse-gas-emission-intensity-of-1/(accessed December 10, 2022)..
[66] IEA Statistics. Electric power transmission and distribution losses (% of output). https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS. [Accessed 12 December 2022].
[67] Cox B, Bauer C, Mendoza Beltran A, van Vuuren DP, Mutel CL. Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios. Appl Energy 2020;269:115021. https://doi.org/10.1016/j.apenergy.2020.115021.
[68] Marques P, Garcia R, Kulay L, Freire F. Comparative life cycle assessment of lithium-ion batteries for electric vehicles addressing capacity fade. J Clean Prod 2019;229:787–94. https://doi.org/10.1016/j.jclepro.2019.05.026.
[69] Shu X, Guo Y, Yang W, Wei K, Zhu G. Life-cycle assessment of the environmental impact of the batteries used in pure electric passenger cars. Energy Rep 2021;7:2302–15. https://doi.org/10.1016/j.egyr.2021.04.038.
[70] Deng Y, Li J, Li T, Gao X, Yuan C. Life cycle assessment of lithium sulfur battery for electric vehicles. J Power Sources 2017;343:284–95. https://doi.org/10.1016/j.jpowsour.2017.01.036.
[71] Studio UNRAE. L'AUTOMOBILE: ITALIANI A CONFRONTO 2022 https://unrae.it/files/Studio%20UNRAE%20L_automobile%20Italiani%20a%20confronto_6336ab4170253.pdf (accessed December 15, 2022)..