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RESEARCH ARTICLE

Lithium-ion battery cell production in Europe

Scenarios for reducing energy consumption and greenhouse gas emissions until 2030

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Abstract

The market for electric vehicles is growing rapidly, and there is a large demand for lithium-ion batteries (LIB). Studies have predicted a growth of 600% in LIB demand by 2030. However, the production of LIBs is energy intensive, thus contradicting the goal set by Europe to reduce greenhouse gas (GHG) emissions and become GHG emission free by 2040. Therefore, in this study, it was analyzed how the energy consumption and corresponding GHG emissions from LIB cell production may develop until 2030. Economic, technological, and political measures were considered and applied to market forecasts and to a model of a state-of-the art LIB cell factory. Notably, different scenarios with trend assumptions and above/below-trend assumptions were considered. It could be deduced that, if no measures are taken and if the status quo is extrapolated to the future, by 2030, ~5.86 Mt CO_2-eq will be emitted due to energy consumption from European LIB cell production. However, by applying a combination of economic, technological, and political measures, energy consumption and GHG emissions could be decreased by 46% and 56% by 2030, respectively. Furthermore, it was found that political measures, such as improving the electricity mix, are important but less dominant than improving the production technology and infrastructure. In this study, it could be deduced that, by 2030, through industrialization and application of novel production technologies, the energy consumption and GHG emissions from LIB cell production in Europe can be reduced by 24%.

KEYWORDS
battery cell production, energy consumption, forecast, greenhouse gas emissions, industrial ecology, technology assessment

1 | INTRODUCTION

1.1 | Importance of the market and lithium-ion battery production

In the global energy policy, electric vehicles (EVs) play an important role to reducing the use of fossil fuels and promote the application of renewable energy. Notably, the EV market is growing rapidly. Many major car manufacturers have announced that they no longer intend to produce combustion

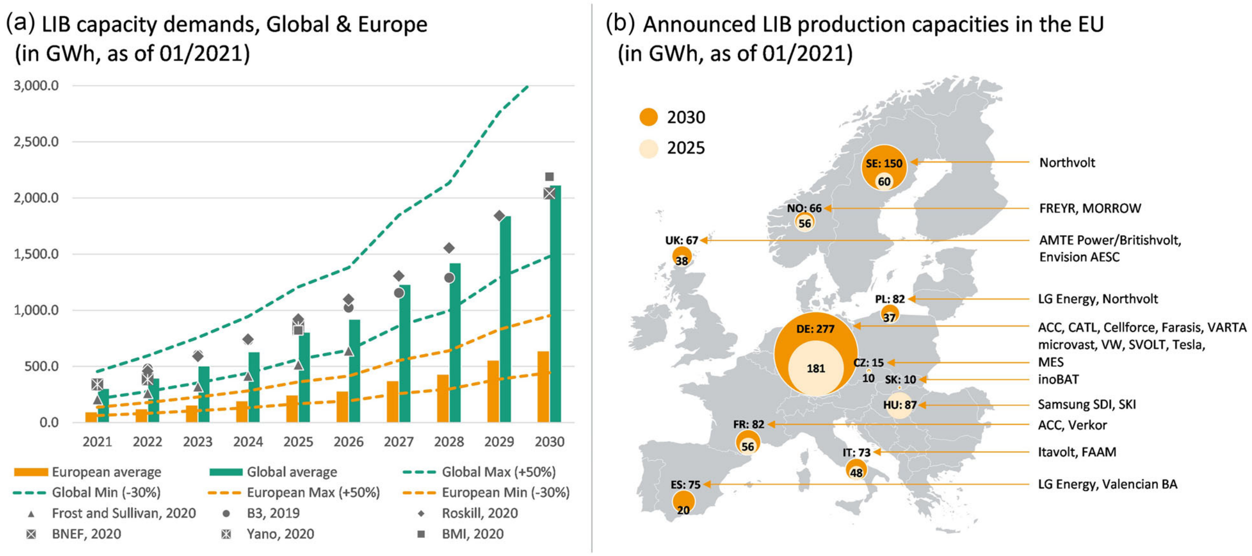

FIGURE 1 (a) Lithium-ion battery (LIB) capacity demands globally and in Europe. (b) Announced cell production capacities in the European Union (EU), based on Hettesheimer et al. (Hettesheimer et al., 2021). The data are available in Supporting Information S1.

engines in the medium-term future and will instead focus entirely on EVs (Forbes, 2021a, 2021b; Reuters, 2021). Consequently, the global market for lithium-ion battery (LIB) cells has grown rapidly. The World Economic Forum predicted a demand of 3500 GWh/a for LIBs by 2030 (World Economic Forum, 2019). Tesla's chief executive officer (CEO) Elon Musk even mentioned a global demand for LIBs of 10,000 GWh/a in the future (Musk, 2020). Hereby, future battery cell factory locations will be in close distance to original equipment manufacturer (OEM), primarily the large automotive companies (Hettesheimer et al., 2021). These are in particular Asia, Europe, and the United States of America. According to predictions made in previous studies, in the future, approximately 25%–30% of the world's LIB cells will be manufactured in Europe (Hettesheimer et al., 2021; Michaelis & Rahimzei, 2020). The global demand for LIBs expected to develop by 2030, especially in Europe, is shown in Figure 1.

The data shown are from a meta-study conducted by the Fraunhofer Institute for Systems and Innovation Research ISI, which uses forecasts and market studies from various market forecast companies (B3, 2021; Benchmark Mineral Intelligence, 2020; BloombergNEF, 2020; Frost & Sullivan, 2020; Roskill, 2021; Yano Research Institute, 2020). Parts of the meta-study, especially for global production, have already been published (Hettesheimer et al., 2021). Zhou et al. (2021) conducted a comparable meta-study, which uses other market forecasts but obtains comparable results. The data can be obtained from Supporting Information S1.

Global battery cell production is currently assumed to grow to 2000 GWh/a by 2030, with a minimum scenario of 1500 GWh/a and a maximum scenario of 3200 GWh/a. A large part of the demand is solely to produce battery cells for EVs (Hettesheimer et al., 2021; Michaelis & Rahimzei, 2020). For Europe, production volumes of approximately 984 GWh/a by 2030 have already been announced (Hettesheimer et al., 2021). However, it must be considered that not all announced projects will be realized until 2030. Nevertheless, by 2030, the battery cell market will increase significantly. This is a major challenge for the European Union (EU), which aims to reduce greenhouse gas (GHG) emissions significantly by 2030 (European Commission, 2021a) and become GHG emission free by 2050 (European Commission, 2021b). On the one hand, EVs support this goal, but on the other hand, LIB production is a new growing market, with significant energy consumption and GHG emissions (Romare & Dahllöf, 2017). Therefore, the European Commission plans to regulate this market, with respect to its ecological aspects, and mandate an ecological battery passport by 2026 (European Commission, 2020). This indicates that LIB production and the related future GHG emissions are strongly relevant and important economic and socio-political topics for sustainable development.

1.2 | Gap in literature

To enable the transition from combustion engines to EVs and generate added ecological value, two things are important: EVs must be powered by electricity from renewable sources and battery cells must be produced as sustainably as possible. Battery cell creation can be separated in material mining, material processing, and in the production of battery cells in battery cell factories. While the mining and processing of materials have various impacts in different environmental categories, the sustainability of a battery cell factory depends mostly on its energy consumption (electricity, natural gas) respectively its resulting GHG emissions expressed in CO_2 equivalents. The reason is that in a battery cell factory all input material is processed to battery cells (output), provided that scrap rate is 0%. Additives such as *N*-methyl-2-pyrrolidone (NMP) and others are processed in closed circuits within the factory. Therefore other environmental impact categories known from LCAs than GHG emissions are not relevant for battery cell factories. However, even for LCAs of LIBs, including material mining and processing, GHG emissions resulting from energy consumption is named as the most important impact category by all major LCA studies (Romare & Dahllöf, 2017).

In a meta-analysis conducted in 2017, the energy consumption and GHG emissions from LIBs were analyzed based on the current life cycle assessment (LCA) literature of that time (Romare & Dahllöf, 2017). The meta-analysis indicated that the energy consumption in LIB cell production varied widely between 350 and 650 MJ/kWh, as is largely caused by battery production. They state that "mining and refining seem to contribute a relatively small amount to the current life cycle of the battery" (Romare & Dahllöf, 2017). The authors concluded that "the currently available data are usually not transparent enough to draw detailed conclusions about the battery's production emissions" (Romare & Dahllöf, 2017). Another comprehensive study (Degen & Schütte, 2022) confirmed this and indicated that this knowledge gap exists to date, especially when it comes to energy consumption of specific production steps in an LIB cell factory.

According to a comprehensive literature review of Degen & Schütte (2022) many relevant LCA studies on the production of LIB cells depend on three major inventories for years 2010 (Notter et al., 2010; Zackrisson et al., 2010), 2011 (Majeau-Bettez et al., 2011), and 2014 (Ellingsen et al., 2014). Many subsequent studies have referred to these primary data and adapted them according to their own considerations. This is particularly apparent in a previous study conducted by Le Varlet et al. (2020), which implements all three studies from 2010, 2011, and 2014. However, in other previous LCA studies (Ambrose & Kendall, 2016; Cusenza et al., 2019; Faria et al., 2014; Kallitsis et al., 2020; Marques et al., 2019; Simon & Weil, 2013; Zhao & You, 2019), the inventories from the LCA studies published in 2010 and 2011 were used as the foundation. Moreover, only certain studies (Cusenza et al., 2019; Dai et al., 2019; Ellingsen et al., 2014; Kallitsis et al., 2020; Kim et al., 2016; Majeau-Bettez et al., 2011; Sun et al., 2020) deal with lithium nickel manganese cobalt oxide (NMC) chemistries, which are state of the art today and most widely used today. Other studies have used other, less important, cell chemistries. This results in the following problems (Degen & Schütte, 2022):

- **Age of analyzed LIB technologies**: A large part of the studies consider obsolete or less important material chemistries that no longer correspond to the current state-of-the-art technology that is widely used. For example, Notter et al. (2010), one of the most important sources of primary LIB data are lithium manganese oxide (LMO) cells. These cells are no longer relevant today and, in industrial practice, they have been almost completely replaced by NMC cells. However, NMC cells have also been further developed from the former NMC111 and NMC333 chemistries to the current NMC622 and NMC811 chemistries. Thus, there have been significant changes in the requirements for production technology, and thus, in the energy consumption of and GHG emissions from battery production.
- **Age of analyzed production technologies**: Even without taking into account the mentioned further development of battery chemistry, production technologies have developed significantly, partly due to the rapid market growth. Notably, new production technologies and economies of scale have significantly increased the production efficiency and reduced the energy consumption during battery production.

Consequently, the most current LCA studies in the scientific literature on the production of LIBs are no longer up to date and should not be used for the ecological analysis of the NMC622 and NMC811 LIBs in today's industrial mass production. More recent studies (Sun et al., 2020) provide own primary data, but with a lack of transparency in terms of the production process and with energy mix data from China. As in other studies, the individual battery cell production steps in a LIB factory are not covered in detail. A study of Erakca et al. (2021) analyzes the energy consumption of these individual battery cell production steps, but only for manufacturing on a laboratory scale and not an industrial scale. As a consequence, their calculated energy consumption for LIB cell production is 35 times higher than that of an LIB cell factory. However, a most recent study by Degen & Schütte (2022) uses own primary data for an LIB cell factory and also provides details and transparency regarding the individual battery cell production steps in an LIB cell factory.

Because there was no reliable data yet in the literature on the energy consumption and GHG emissions of current industrial NMC-based battery cell production for each individual production step in a LIB cell factory, there could not be reliable forecasts of future energy consumption neither. This is apparent in a commercial forecast study by Whattoff et al. (2021), which uses data from Dai et al. (2019) and therefore assumes GHG emissions three times larger than calculated by Degen and Schütte (2022) for a state-of-the-art LIB cell factory. In addition, the study lacks background details and only considers the impact of the change in electric energy mix. Further forecast studies are currently not available. Consequently, there is currently no reliable knowledge available on how the energy consumption of LIB cell production will develop in the future, on the factors that may have a significant effect on LIB cell production, and on measures that can reduce the GHG emissions of LIB cell factories. However, by the recent study of Degen and Schütte (2022) such forecasts were made possible and will be addressed in this paper.

1.3 | Focus of study and research goal

In this study the comprehensive battery cell production data of Degen and Schütte (2022) was used to estimate the energy consumption of and GHG emissions from battery production in Europe by 2030. In addition, it was possible to analyze and propose new methods to suggest how the government and battery cell producers themselves could make battery production more sustainable.

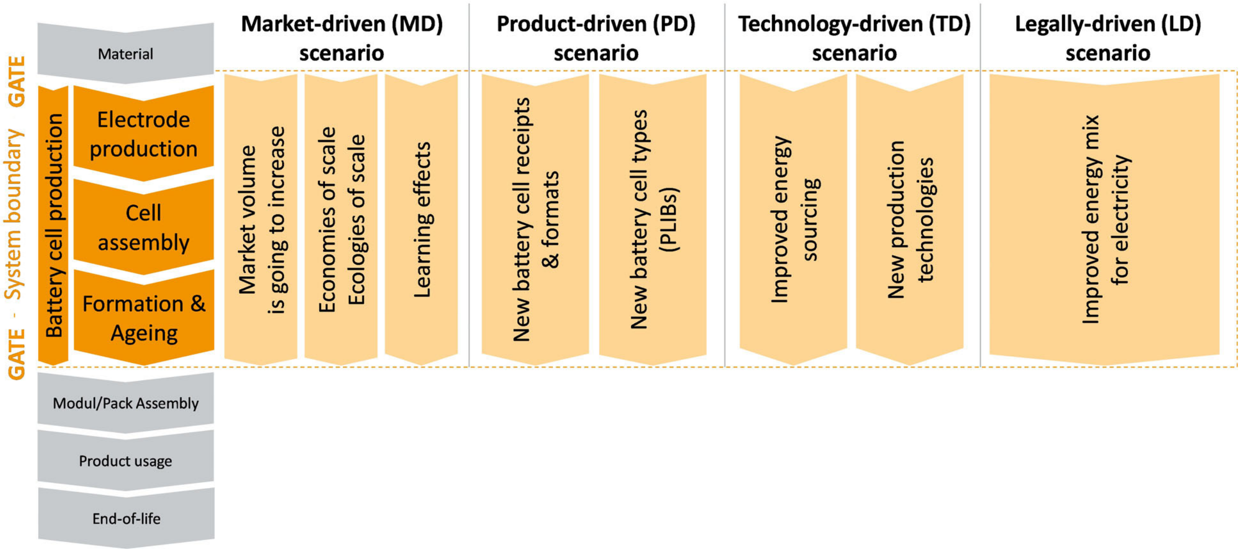

FIGURE 2 Scenarios analyzed in this study, along with their factors and the system boundary of this study; market-driven (MD), product-driven (PD), technology-driven (TD), legally driven (LD) scenarios.

Because battery cell production is still relatively in its early technological stages, there is much potential to improve efficiency, energy consumption, and corresponding GHG emissions in battery cell production. The study is structured analogously to Reißmann et al. (2021). Analogously, four different scenarios that may have a significant impact on improving the energy consumption and corresponding GHG emissions of battery cell production were analyzed (Figure 2):

- **Market-driven (MD) scenario**: In this scenario, the strong growth of the battery cell market, which is expected to reach up to 600% of the current level by 2030 was taken into account (Hettesheimer et al., 2021; Zhou et al., 2021). Notably, market growth alone results in an absolute increase in the energy consumption in and GHG emissions from LIB cell production. Additionally, economies of scale will also exist because of the increase in production volume, resulting from the synergies in production, which improves production efficiency. This also has an effect on energy consumption and is known as "ecologies of scale" (Schlich & Fleissner, 2005). Another factor is "learning effects" which is a process of improving results and earning through education. Notably, this is different from economies of scale because learning effects depend on not only the annual production volume but also the cumulative quantity of LIB cells produced (Henderson, 1968). Through learning effects, existing production technologies can be used more efficiently.
- **Product-driven (PD) scenario**: Over the past years, batteries are constantly being developed and improved, particularly driven by high market growth. For example, the LMO cell chemistries analyzed by Notter et al. (2010) have become less important today and will become obsolete in the near future; they will most probably be replaced by NMC chemistries, such as NMC811. Further developments in cell chemistries and cell formats can cause significant changes in the production infrastructure and, therefore, energy consumption. However, the upcoming new battery cell type, post lithium-ion batteries (PLIBs), will prove to be more important. These are, for example, the solid-state batteries (SSBs), sodium-ion batteries (SIBs), lithium-sulfur batteries (LSBs), and lithium-air batteries (LABs). In most cases, these new battery types require new production technologies (Duffner et al., 2021). This will significantly affect the energy consumption in and GHG emissions from battery cell production in the future.
- **Technology-driven (TD) scenario**: The efficiency of battery cell production can be further improved by optimizing the use of existing production technologies and enhancing the production technologies themselves. There are many novel production technologies that have the ability to significantly reduce the energy consumption and cost in LIB cell production in the near future (Duffner et al., 2021; Michaelis & Rahimzei, 2020). Michaelis and Rahimzei (2020) provided a comprehensive overview about promising technologies in LIB cell production that are currently in development or even available as prototypes. In this study, the effects of four novel and most promising LIB cell production technologies, with the highest impact on economic and ecologic key performance indicators (KPIs) in LIB cell production, were analyzed. In addition to development and application of new production technology, other energy sources can be used, for example, replacing fossil fuels with green electricity or other forms of energy. However, this requires changes in production technologies.
- **Legally driven (LD) scenario**: The EU is committed to significantly reduce GHG emissions by 2030 (European Commission, 2021a) and avoid it completely by 2050 (European Commission, 2021b). Consequently, there is a wide range of policy measures in Europe to move away from fossil

TABLE 1 Process-specific energy consumption in battery cell manufacturing, based on data obtained from Degen and Krätzig (2022b) and Degen and Schütte (2022).

#	Production step	Electric energy consumption per battery cell capacity [kWh_{elec}/kWh_{cell}]	Natural gas energy consumption per battery cell capacity [kWh_{gas}/kWh_{cell}]
01	Mixing	0.13	0.00
02	Coating and drying	0.92	10.10
03	Calendering	0.53	0.00
04	Slitting	0.16	0.00
05	Vacuum drying	0.04	1.57
06	Winding	0.25	0.00
07	Assembling	1.59	0.00
08	Washing	1.98	0.00
09	Formation	9.92	0.25
10	Aging	0.00	0.40
11	Testing	0.99	0.00
–	Handling	1.98	0.00
–	Dry rooms	1.62	9.06
	Sum	20.11	21.37
	Total sum	41.48	

fuels to renewable energy. The most important measure is to increase the renewable energy share in the electricity mix, promoted by various political support instruments, such as subsidies and sanctions. For battery cell production, this indicates that, in the future, electricity will have a higher share of renewable energy, and the use of fossil fuels in production will be a limited (European Commission, 2021a, 2021b).

It is important to mention that the given scenarios can affect each other. For example, new and improved batteries lead to increased market demand, and increased market demand leads to increased motivation to invest money in the development of new and improved batteries. For reasons of complexity, in this study, only the main effects of these scenarios were considered. In addition, it is also important to mention that the assessment of the material is not included in this study. The study is focusing in particular on a gate-to-gate value chain.

In this study, the goal was to analyze how different scenarios may affect energy consumption in and GHG emissions from European battery cell production until 2030. In addition, I investigated measures that had the potential to promote more sustainable battery cell production. Because the battery cell is the main component of EVs and the EV market will grow significantly in future, the socio-environmental relevance of European battery cell production is considered as being very high.

2 | METHODS AND DATA

2.1 | Base case and reference technology

To estimate the future development of energy consumption and GHG emissions in LIB cell production, a base case is required that portrays the current state-of-the-art LIB cell production and manufacturing data. For this study as base case data from Degen and Krätzig (2022b) and Degen and Schütte (2022) was used. Degen and Krätzig (2022b) got access to a state-of-the-art LIB cell factory in Europe and provided all machinery data as well as an economic analysis. Degen and Schütte (2022) used this machinery data for an ecological analysis of a battery cell factory in terms of energy consumption and GHG emission. The analyzed factory line had a production output of 200 battery cells per minute (cylindrical, format 21700, NMC622 chemistry). The energy consumption of each production step of the LIB cell which was obtained in the named studies is shown in Table 1. The corresponding data and manufactured LIB cell data are available in Supporting Information S2.

In LIB cell production, a large amount of electrical energy is required. The battery cells are charged and discharged several times to form a solid electrolyte interphase (SEI) layer, which enables the battery cell to function (An et al., 2016). This step is very energy intensive because of the charging and discharging losses during the formation process. Notably, when thermal energy is required, natural gas is generally used for battery cell production; these include various drying processes and the requirement of high-temperature (HT) storage during aging. Approximately 41 kWh

TABLE 2 Criteria for assessment of future lithium-ion battery (LIB) cell production scenarios in terms of energy consumption and greenhouse gas (GHG) emissions.

Criteria	Description	Symbol	Unit
Absolute energy consumption of the annual production	Amount of energy required to produce the annual market volume of LIBs	E_{year}	GWh/a
Cell-specific energy consumption of the production	Amount of energy required to produce 1 kWh of battery cell capacity	E_{cell}	kWh/kWh_{cell}
» Thereof electricity	*Amount of energy of electricity required to produce 1 kWh of battery cell capacity*	E_{cell_elec}	kWh_{elec}/kWh_{cell}
» Thereof natural gas	*Amount of energy of natural gas required to produce 1 kWh of battery cell capacity*	E_{cell_gas}	kWh_{gas}/kWh_{cell}
Absolute GHG emissions from annual production	Amount of GHG emissions resulting from the production of the annual market volume of LIB cells resulting from the energy consumption required for production	m_{GHG_year}	CO_2-eq/a
Cell-specific GHG emissions of the production	Amount of GHG emissions resulting from the production of 1 kWh of battery cell capacity	m_{GHG_cell}	CO_2-eq/kWh_{cell}

of energy is required to produce 1 kWh of battery cell capacity, excluding the energy required by the material (Degen & Schütte, 2022). The numbers used in this study represent the "base case" for deriving the other possible future scenarios mentioned in this study.

2.2 | Data and assessment criteria

In this step, the criteria applied for the assessment of future LIB cell manufacturing scenarios are defined. For this, the same criteria as that applied by Degen and Schütte (2022) for the ecological assessment of the current state-of-the-art LIB cell production are used. The assessment criteria are presented in Table 2.

In this study, only ecological assessment parameters of a batter cell factory were considered. As written in chapter 1.2 these are in particular electricity and natural gas consumption and their corresponding GHG emissions. In the production of LIB cells these account for approximately one fourth of the manufacturing costs (Degen & Krätzig, 2022b). Therefore, a reduction in energy consumption also leads to a reduction in the production costs. However, this could not be quantified due to the uncertain development of future energy costs, future criteria for financial sanctioning of GHG emissions, and future composition of the LIB cells.

2.3 | Factor effects on assessment criteria

In this section, the factors that probably have the most significant effects on the assessment criteria are named and described. These factors correspond to those shown in Figure 2. In addition to the figure, the factor "new production technologies" is divided into four specific technology approaches. For the four process steps that consume the most energy in LIB cell production (coating and drying, formation, aging, and dry rooms; see Table 1), the most promising technology innovations were selected. It could be estimated that by applying these four specific technological innovations, a significant reduction in the energy consumption in LIB cell production may be possible in the future. Notably, the selection and evaluations of these technologies were derived from previous studies conducted on LIB cell production (Degen & Krätzig, 2022a).

In total, 11 factors (F1–F11) were identified, which may have major effects on the assessment criteria defined in Table 2. Notably, the list of factors, their explanation, and the assumptions of their effects on the assessment criteria are provided in Table 3. For each factor, an average effect was assumed (trend), while considering an above-average (high) and below-average (low) effect. In addition, for each factor it is indicated which assessment criteria are directly influenced by it. The theoretical basis as well as all calculations can be found in Supporting Information S3.

3 | RESULTS AND DISCUSSION

Notably, from the 11 identified factors (F1–F11), only 9 factors will have significant impacts on the assessment criteria. Factor F4 (new battery cell recipes and formats) has only a minor effect on the assessment criteria, and F5 (new battery cell types) will not change significantly enough by 2030

TABLE 3 Scenario factors and assumptions for analyzing the factor effects on assessment criteria.

Factor *(Scenario)*	Assumptions	Effects on assessment criteria and assumptions
F1: Market/production increase *(MD-scenario)*	*Development of market until 2030*: • Trend: According to Figure 1 • High: +50% above trend • Low: −30% below trend	Direct effects on: • Absolute energy consumption • Absolute GHG emissions References: (Frith, 2021), (Hettesheimer et al., 2021, (Zhou et al., 2021))
F2: Economies of scale/ ecologies of Scale *(MD-scenario)*	*Reduction of energy consumption*: • Trend: −4% per doubled output • High: −5% per doubled output • Low: −3% per doubled output	Direct effects on: • Cell-specific energy consumption • Cell-specific GHG emissions Affected by: • Market/production increase (annual) References: ((Mauler et al., 2021; O'Sullivan et al., 2002), (Schlich & Fleissner, 2005))
F3: Learning effects *(MD-scenario)*	*Reduction of energy consumption*: • Trend: −4% per doubled output • High: −5% per doubled output • Low: −3% per doubled output	Direct effects on: • Cell-specific energy consumption • Cell-specific GHG emissions Affected by: • Market/production increase (cumulated) Reference: (Stewart et al., 1995)
F4: New battery cell recipes and formats *(PD-scenario)*	*Annual increase of areal electrode energy density and thus reduction of energy consumption in production to achieve market demand* • Trend: −4% until 2030 • High: −5% until 2030 • Low: −3% until 2030	Direct effects on: • Cell-specific energy consumption • Cell-specific GHG emissions References: ((Bhandari et al., 2022; Michaelis & Rahimzei, 2020))
F5: New battery cell types *(PD-scenario)*	*Share of used energy until 2030*: • n/a	Direct effects on: • Cell-specific energy consumption • Cell-specific GHG emissions References: ((Bhandari et al., 2022; Duffner et al., 2021))
F6: Improved energy sourcing *(TD-scenario)*	*Share of used energy until 2030*: • Trend: 49% electricity, 51% natural gas • High: 100 % electricity, 0% natural gas • Low: 48% electricity, 52% natural gas	Direct effects on: • Cell-specific energy consumption • Cell-specific GHG emissions Reference: (Degen & Schütte, 2022)
F7: New technology, "Dry coating" *(TD-scenario)*	*Technology related parameters*: • Process step: Coating and drying • Market entry: 2024 • Effect: −100% thermal energy *Market share until 2030*: • Trend: +7%/a market penetration • High: +10%/a market penetration • Low: +4%/a market penetration	Direct effects on: • Cell-specific energy consumption • Cell-specific GHG emissions References: (Degen & Krätzig, 2022a), (Kwade et al., 2018), (Musk, 2020)
F8: New technology, "Fast formation cycling" *(TD-scenario)*	*Technology related parameters*: • Process step: Formation • Market entry: 2022 • Effect: −40% electric energy *Market share until 2030*: • Trend: 10%/a market penetration • High: 15%/a market penetration • Low: 5%/a market penetration	Direct effects on: • Cell-specific energy consumption • Cell-specific GHG emissions Reference: (An et al., 2017)
F9: New technology, "Self-discharge analyzing" *(TD-scenario)*	*Technology related parameters*: • Process step: (High temperature) aging • Market entry: 2022 • Effect: −100% thermal energy *Market share until 2030*: • Trend: 5%/a market penetration • High: 7%/a market penetration • Low: 2%/a market penetration	Direct effects on: • Cell-specific energy consumption • Cell-specific GHG emissions References: ((Al-Zubaidi R-Smith et al., 2021; Degen & Krätzig, 2022b))

(Continues)

TABLE 3 (Continued)

Factor *(Scenario)*	Assumptions	Effects on assessment criteria and assumptions
F10: New technology, "Mini-environments" *(TD-scenario)*	*Technology related parameters*: • Process step: Dry rooms • Market entry: 2023 • Effect: −65% thermal energy *Market share until 2030*: • Trend: 5%/a market penetration • High: 7%/a market penetration • Low: 2%/a market penetration	Direct effects on: • Cell-specific energy consumption • Cell-specific GHG emissions References: ((Degen & Krätzig, 2022b), (Duffner et al., 2021), (Kwade et al., 2018), Michaelis & Rahimzei, 2018), (PEM of RWTH Aachen, 2017)
F11: Improved electricity energy mix *(LD-scenario)*	*Share of renewable energy until 2030*: • Trend: GER: 65%, EU: 5 7% • High: GER: 70%, EU: 62% • Low: GER: 60%, EU: 52%	Direct effects on: • Cell-specific GHG emissions References: ((Buck et al., 2019 (German Ministry of Economic Affairs & Energy, BMWi), Redl et al., 2021))

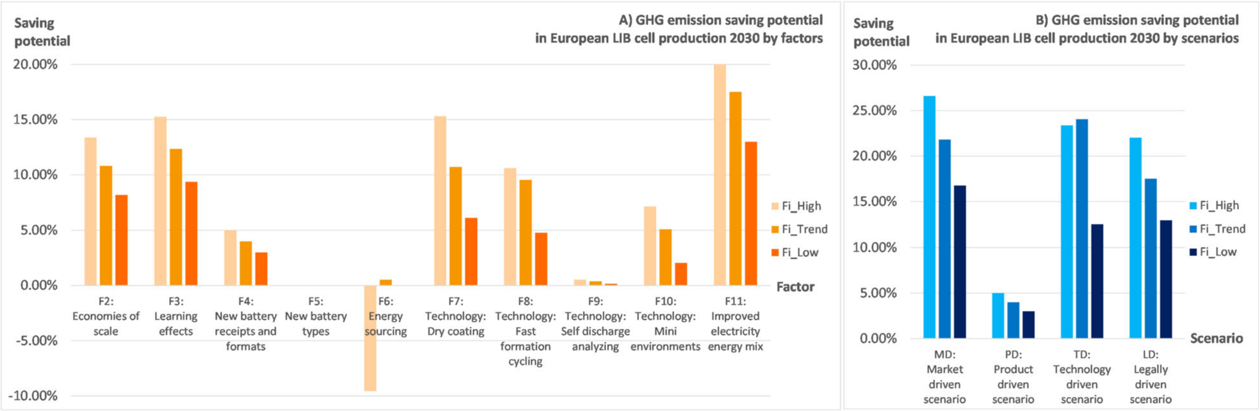

FIGURE 3 (a) Effect of the factors on greenhouse gas (GHG) emission saving potential in European LIB cell production by 2030 (excluded F1); (b) contribution of the four scenarios on greenhouse gas (GHG) emission saving potential in European LIB cell production by 2030; market-driven (MD), product-driven (PD), technology-driven (TD), and legally driven (LD) scenarios. The data are available in Supporting Information S4.

(Duffner et al., 2021; Michaelis & Rahimzei, 2020) to have a major impact on the assessment criteria. However, when using three factor levels and a full factorial analysis, $3^9 = 19{,}683$ factor combinations, and thus, 19,683 different future scenarios, are possible. To reduce complexity, first, only the main effects of the factors were analyzed, ceteris paribus. The possible interactions between these factors have not yet been considered.

The factors affecting GHG emissions in Europe by 2030 are shown in Figure 3. In this figure, the factor F1 (market development) is not considered, because this is the basis for the calculation of all factor effects. The complete calculations are provided in Supporting Information S4.

Figure 3 indicates that all factors affect the GHG savings potential to different degrees. As mentioned before, the factor F5 has no effect on the GHG emissions from LIB cell production until 2030. Particularly noticeable is the factor F6 (energy sourcing): for a single factor variation of F6-high (full use of electric energy and no use of natural gas), the GHG emissions in 2030 will be even higher than today. The reason for this is that only the main effect was considered: a full switch to electricity instead of natural gas, but with a current electricity mix. Today, heat generated by natural gas has less GHG emissions than the generation of the same amount of heat energy by electricity. However, by 2025 in the EU and probably 2030 in Germany, the kWh of electricity should have less CO_2 emissions than a kWh of heat produced by natural gas, when assuming a linear change. At these break-even points, the use of electricity as the sole energy source makes more ecological sense. Notably, this depends on the prices of electricity and natural gas in the future, as well as on the cost of CO_2 certificates.

The ranking of the factors with the greatest single effect on potential GHG emissions savings in 2030 is as follows (descending order):

1.	New production technologies	
1.1.	"Dry coating" technology	(F7)
1.2.	"Fast formation cycling" technology	(F8)
1.3.	"Mini environments" technology	(F10)
1.4.	"Self-discharge analysis" technology	(F9)
2.	Improved energy sourcing	(F6)
3.	Improved electricity energy mix	(F11)
4.	Learning Effects	(F3)
5.	Economies of scale	(F2)
6.	New battery cell recipes and formats	(F4)
7.	New battery cell types	(F5)

Based on the impact of the scenarios mentioned in Figure 2, the ranking results (descending order for trend scenarios) are as follows:

1.	Technology-driven scenario	(–24.1%)
2.	Market-driven scenario (excluding the market growth itself)	(–21.8%)
3.	Legally driven scenario	(–17.5%)
4.	Product-driven scenario	(–4%)

The largest potential to reduce GHG emissions from the (TD) scenario is the combination of novel production technologies with heat pumps to eliminate the need for natural gas, which results in an average GHG savings potential of –24.08% by 2030. Market-driven (MD) effects may also result in significant savings potentials of –21.81% on average. The plans of the EU and member countries, such as Germany, to significantly increase the share of renewable energy in the electricity mix by 2030 (LD scenario) can result in a GHG savings potential of –17.52%. Product-driven (PD) effects will have only a minor impact of –4% on European GHG emissions by 2030; however, they are expected to significantly influence LIB cell production and GHG emissions after 2030.

In this study, for ranking, only the main effects have been considered. Furthermore, only the effects in 2030 are discussed. Therefore, it was calculated how the factors may affect the energy consumption and GHG emissions in LIB cell production from today to 2030. Notably, not only the main effects but also all interactions between the factor variations were considered. Because interactions by definition cannot be attributed to a single factor variation, the factors with the highest significance were applied first in the calculation, and the effects with lower significance were applied subsequently. The corresponding calculations are presented in Supporting Information S4. The calculated results for the average assumptions (trends) are shown in Figure 4. First, it is explained how "Cell specific energy consumption of the production (E_{cell})" may develop by 2030, along with predicting the shares of electric power and natural gas (Figure 4a). Then, it was explained how the "absolute energy consumption of the annual production (E_{year})" may develop by 2030 and the shares of various factors that have energy saving potential (Figure 4b). Finally, the "absolute GHG emissions from the annual production (m_{GHG_year})" that may develop by 2030 was portrayed, along with the shares of different factors that have GHG emission saving potential (Figure 4c).

As shown in Figure 4a, by combining all the factors (F1–F11), by 2030, the cell-specific energy consumption of the production E_{cell} can be reduced from 41.48 to 22.58 kWh/kWh$_{cell}$. This is a 46% reduction compared to the current level. In 2021, 52% of the energy demand is covered by natural gas; in 2030, electricity will have a higher share of 55%. The factors that have an impact on this shift from natural gas to electricity are dry coating technology (F7), mini environment technology (F10), self-discharge analyzing technology (F10), and the use of heat pumps (F6). Notably, all relevant factors are technology related and are part of the TD scenario.

As shown in Figure 4b, the energy consumption in LIB cell production will increase from 3775 GWh/a in 2021 to 26,320 GWh/a in 2030, if cell-specific energy consumption is not improved. By combining all factors, energy consumption in 2030 can be almost halved, resulting in an energy consumption of 14,918.04 GWh/a by 2030. Of these, approximately 8205 GWh are covered will be electricity (55%) and approximately 6718 GWh by natural gas (45%). The biggest impacts are from the factors from the TD scenario (F6, F7, F8, F9, and F10). The improvement in the electric energy mix has no effect on energy consumption. The economies of scale (F2) and learning effects (F3) cause further reduction. In total, in the trend scenario, a reduction of 43% is estimated by the factors F2–F11.

As shown in Figure 4c, the GHG emissions will increase, owing to the strongly growing market and production output. Without significant measures in 2030, 5.86 Mt CO_2-eq of GHG emission will be emitted. However, according to the measures F2–F11, the corresponding GHG emissions can be reduced significantly; by 2030, the annual emissions of GHG emissions could be reduced by almost 54%. The largest contribution to GHG

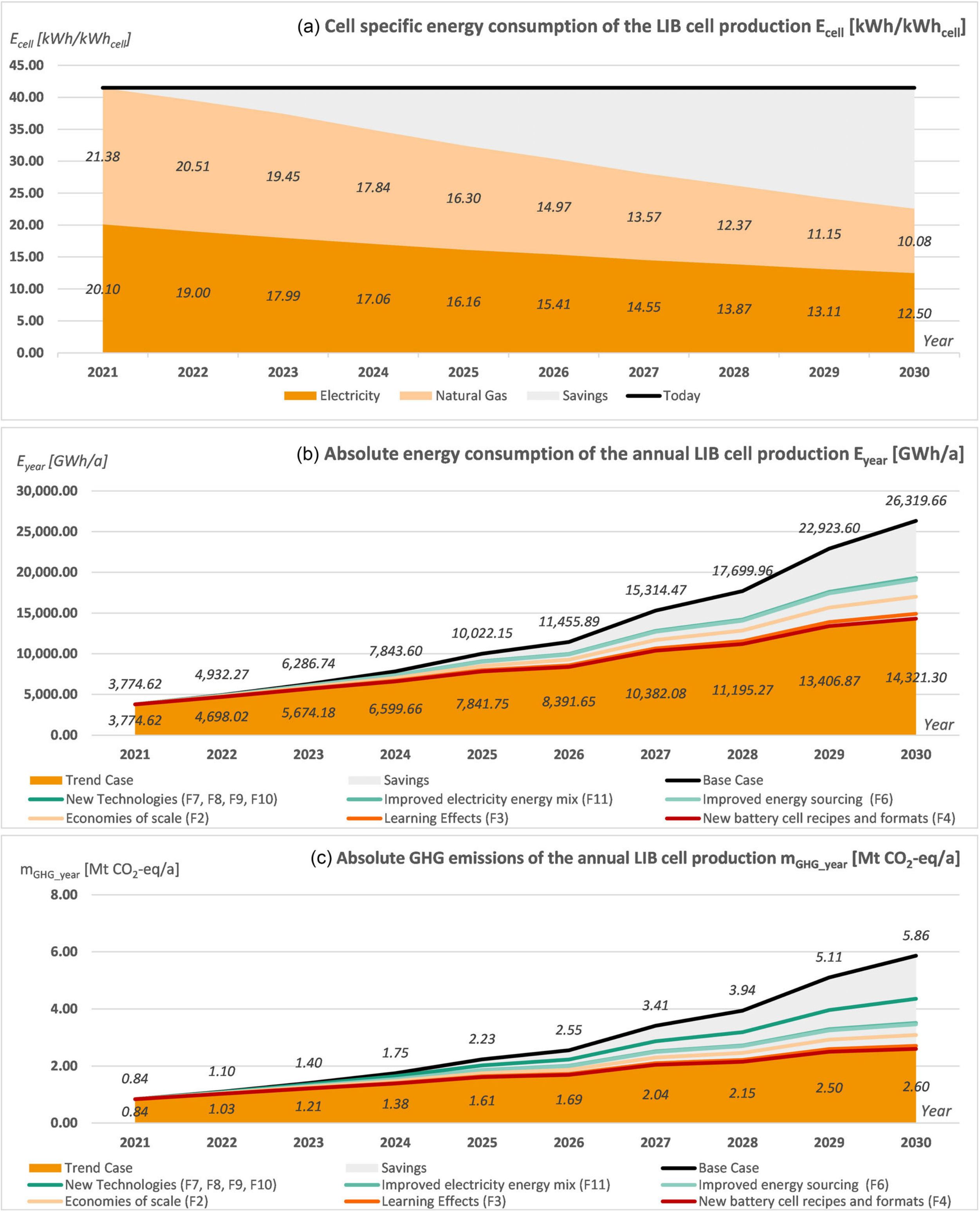

FIGURE 4 Development of (a) the cell-specific energy consumption in lithium-ion battery (LIB) cell production in Europe; (b) absolute energy consumption in LIB cell production in Europe; and (c) absolute greenhouse gas (GHG) emissions from the annual LIB cell production in Europe. The data are available in Supporting Information S4.

savings is from the TD scenario (F6, F7, F8, F9, and F10). The second largest contribution is from the improved electricity energy mix (F11), enabling the EU to achieve its self-declared climate goals (European Commission, 2021a, 2021b). In addition, the learning and scale effects (F2 and F3) will contribute to a significant reduction in GHG emissions. In total, when cumulating the effects of F2–F11 during 2021—2030, 11.14 Mt CO_2-eq could be saved by 2030 in European LIB cell production. This is almost four times the GHG emission in 2030, with notable improvements, and twice the GHG emission in 2030, without improvements.

However, it should be noted that future predictions are always uncertain. However, it was observed that small changes in the factor values influenced the assessment criteria. A combination of variation changes different from the trend scenario could, therefore, change the forecast significantly. Nevertheless, the trend scenario was chosen carefully, and there could be variations in the increase and decrease of the emissions. Notably, the results obtained in this study are good indicators for estimating future development, but the exact numbers need to be deduced carefully.

It is important to mention that energy consumption of LIB cell factories and its corresponding GHG emissions are only a part of a full LCA of LIB cells. For instance material mining, material processing and also the end of life (EOL) are also important life cycle phases which are not addressed in this study. It is assumed that in average 50% (Romare & Dahllöf, 2017) till 70% (Whattoff et al., 2021) of energy in a full life cycle of a LIB cell corresponds to material mining and processing. Therefore it is not just important to reduce the GHG emissions of LIB cell factories, but also to ensure that the material is mined and processed with low GHG emissions. Although there are also other impact categories relevant in LCAs of LIB cells, many researchers name the energy consumption respectively the corresponding GHG emissions as the most important impact categories (Romare & Dahllöf, 2017). Both the limitation of the system boundary and of the impact categories of this study have to be taken into account when using this study for further decision making. However, regarding the limitations, the given results can be used as an important element for future full LCAs of LIBs.

4 | CONCLUSION AND IMPLICATIONS

The market for LIBs and, therefore, the production of LIB cells is increasing rapidly. Studies have deduced that, in Europe, if no measures are taken, this will lead to cumulated GHG emissions of 28.20 Mt CO_2-eq during 2021—2030 and annual GHG emissions of 8.86 Mt CO_2-eq/a by 2030. This development contradicts the goal of the EU and its member states to be “climate neutral” until 2050 (European Commission, 2021b). Therefore, strong measures must be taken to achieve these goals and reduce GHG emissions from LIB cell production. In this study, different scenarios that can help reduce the future GHG emissions in the EU were studied. The main results of this study can be summarized as follows:

1. In European LIB cell production, the energy consumption and GHG emissions will increase by almost 600% by 2030 if no measures are taken.
2. By applying a mix of political, economic, and technological measures, by 2030, energy consumption and GHG emissions (with respect to LIB cell production) could be decreased by 46 % and 56%, respectively.
3. Notably, before 2030, changes in battery cell chemistry and battery cell formats will have no significant effects on energy consumption in and GHG emissions from LIB cell production.
4. The EU-wide increase in the share of renewable energy in the electricity mix is an important measure, but it is not the most effective measure to reduce GHG emissions from LIB cell production.
5. The most important measure to reduce the related energy consumption and GHG emissions is industrialization and the application of new production technologies.
6. By applying new production technology in the three production steps/environments that have the highest energy consumption (coating/drying, formation, and dry rooms), energy consumption and GHG emissions could be decreased by 24% by 2030.
7. Public funding programs should envisage new projects to improve production technology. Special focus should be on introducing new technologies and methods for coating/drying and formation processes and dry rooms, considering the fact that promising approaches are already available at a pre-industrial development stage.

Because the future is uncertain and the battery market is highly dynamic, I recommend updating this study in the future. Notably, the changing market forecasts and the introduction of new production technologies must be considered. In addition, I recommend applying my method to forecast LIB cell production in other regions, and to extent the system boundaries, for example, by adding the material mining, the material processing, and the end-of-life phase. The calculation model, which is available in the Supporting Information, can be used for this purpose. However, the presented results can be the basis for further research in the field of LCAs, especially in electromobility, second-use applications, and recycling.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the Supporting Information of this article.

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REFERENCES

Al-Zubaidi R-Smith, N., Leitner, M., Alic, I., Toth, D., Kasper, M., Romio, M., Surace, Y., Jahn, M., Kienberger, F., Ebner, A., & Gramse, G. (2021). Assessment of lithium ion battery ageing by combined impedance spectroscopy, functional microscopy and finite element modelling. *Journal of Power Sources*, *512*(14), 230459. https://doi.org/10.1016/j.jpowsour.2021.230459

Ambrose, H., & Kendall, A. (2016). Effects of battery chemistry and performance on the life cycle greenhouse gas intensity of electric mobility. *Transportation Research Part D: Transport and Environment*, *47*(9), 182–194. https://doi.org/10.1016/j.trd.2016.05.009

An, S. J., Li, J., Daniel, C., Mohanty, D., Nagpure, S., & Wood, D. L. (2016). The state of understanding of the lithium-ion-battery graphite solid electrolyte interphase (SEI) and its relationship to formation cycling. *Carbon*, *105*(4), 52–76. https://doi.org/10.1016/j.carbon.2016.04.008

An, S. J., Li, J., Du, Z., Daniel, C., & Wood, D. L. (2017). Fast formation cycling for lithium ion batteries. *Journal of Power Sources*, *342*, 846–852. https://doi.org/10.1016/j.jpowsour.2017.01.011

B3 Corporation. (2021). LIB materials market bulletin. (21Q1).

Benchmark Mineral Intelligence. (2020). *2020 Cost challenges for NCAM and the benefits of more supply, 2020 nickel-intensive cathodes and the longer-term challenge of supply*. https://www.benchmarkminerals.com/

Bhandari, N., Cai, A., Yuzawa, K., Zhang, J., Joshi, V., Fang, F., Lee, G., Harada, R., & Shin, S. (2022). *Batteries: The greenflation challenge*. https://www.goldmansachs.com/insights/pages/batteries-the-greenflation-challenge.html

BloombergNEF. (2020). *Battery pack prices cited below $100/kWh for the first time in2020, while market average sits at $137/kWh*. https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/

Buck, M., Graf, A., & Graichen, P. (2019). *European energy transition 2030: The big picture: Ten priorities for the next European commission to meet the EU's 2030 targets and accelerate towards 2050*. https://www.agora-energiewende.de/fileadmin/Projekte/2019/EU_Big_Picture/153_EU-Big-Pic_WEB.pdf

Cusenza, M. A., Bobba, S., Ardente, F., Cellura, M., & Di Persio, F. (2019). Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles. *Journal of Cleaner Production*, *215*, 634–649. https://doi.org/10.1016/j.jclepro.2019.01.056

Dai, Q., Kelly, J. C., Gaines, L., & Wang, M. (2019). Life cycle analysis of lithium-ion batteries for automotive applications. *Batteries*, *5*(2), 48. https://doi.org/10.3390/batteries5020048

Degen, F., & Krätzig, O. (2022a). Future in battery production: An extensive benchmarking of novel production technologies as guidance for decision making in engineering. *IEEE Transactions on Engineering Management*. https://doi.org/10.1109/TEM.2022.3144882

Degen, F., & Krätzig, O. (2022b). Modelling large scale manufacturing of automotive battery cells – Impact of new technologies on production economies. *IEEE Transactions on Engineering Management*. https://dx.doi.org/10.2139/ssrn.4019171

Degen, F., & Schütte, M. (2022). Life cycle assessment of the energy consumption and GHG emissions of state-of-the-art automotive battery cell production. *Journal of Cleaner Production*, 330.

Duffner, F., Kronemeyer, N., Tübke, J., Leker, J., Winter, M., & Schmuch, R. (2021). Post-lithium-ion battery cell production and its compatibility with lithium-ion cell production infrastructure. *Nature Energy*, *6*(2), 123–134. https://doi.org/10.1038/s41560-020-00748-8

Ellingsen, L. A.-W., Majeau-Bettez, G., Singh, B., Srivastava, A. K., Valøen, L. O., & Strømman, A. H. (2014). Life cycle assessment of a lithium-ion battery vehicle pack. *Journal of Industrial Ecology*, *18*(1), 113–124. https://doi.org/10.1111/jiec.12072

Erakca, M., Baumann, M., Bauer, W., de Biasi, L., Hofmann, J., Bold, B., & Weil, M. (2021). Energy flow analysis of laboratory scale lithium-ion battery cell production. *IScience*, *24*(5), 102437. https://doi.org/10.1016/j.isci.2021.102437

European Commission. (2021a). *2030 Climate & energy framework*. https://ec.europa.eu/clima/policies/strategies/2030_en

European Commission. (2021b). *2050 Long-term strategy*. https://ec.europa.eu/clima/policies/strategies/2050_en

European Commission. (2020). Proposalfor a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning batteries and waste batteries, repealing Directive 2006/66/ECand amending Regulation (EU) No 2019/1020. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0798.

Faria, R., Marques, P., Garcia, R., Moura, P., Freire, F., Delgado, J., & Almeida, A. T. D. (2014). Primary and secondary use of electric mobility batteries from a life cycle perspective. *Journal of Power Sources*, *262*(17), 169–177. https://doi.org/10.1016/j.jpowsour.2014.03.092

Forbes. (2021a). *GM plans to phase out gas and diesel cars by 2035*. https://www.forbes.com/wheels/news/gm-phase-out-gas-diesel-cars-2035/

Forbes. (2021b). *Volvo cars joins anti-combustion engine crowd, will be all-electric by 2030*. https://www.forbes.com/sites/sebastianblanco/2021/03/02/volvo-joins-anti-combustion-engine-crowd-will-be-all-electric-by-2030/?sh=1ba407482cb6

Frith, J. (2021). Production delays lead some automakers to try a low-cost, low-range battery. *Bloomberg*. https://www.bloomberg.com/news/newsletters/2021-09-07/production-delays-lead-some-automakers-to-try-a-low-cost-low-range-battery

Frost & Sullivan. (2020). *Global Li-ion battery materials market, forecast to 2026*. https://store.frost.com/global-li-ion-battery-materials-market-forecast-to-2026.html

German Ministry of Economic Affairs and Energy BMWi. (2019). Renewable energy. https://www.bmwi.de/Redaktion/EN/Dossier/renewable-energy.html

Henderson, B. (1968). The experience curve (Perspectives No. 16). https://image-src.bcg.com/Images/Experience_Curve_1968_tcm9-140279.pdf

Hettesheimer, T., Wietschel, M., Neef, C., Stijepic, D., Moll, C., Thielmann, A., TerceroEspinoza, L., & Joachimsthaler, C. (2021). Batteriestandort auf Klimakurs: Perspektiven einer klimaneutralen Batterieproduktion für Elektromobilität in Deutschland. Studie. https://www.agora-verkehrswende.de/fileadmin/Projekte/2021/Klimaneutrale-Batterieproduktion/59_klimaneutrale_Batterieproduktion.pdf

Kallitsis, E., Korre, A., Kelsall, G., Kupfersberger, M., & Nie, Z. (2020). Environmental life cycle assessment of the production in China of lithium-ion batteries with nickel-cobalt-manganese cathodes utilising novel electrode chemistries. *Journal of Cleaner Production*, *254*(2), 120067. https://doi.org/10.1016/j.jclepro.2020.120067

Kim, H. C., Wallington, T. J., Arsenault, R., Bae, C., Ahn, S., & Lee, J. (2016). Cradle-to-gate emissions from a commercial electric vehicle Li-ion battery: A comparative analysis. *Environmental Science & Technology*, *50*(14), 7715–7722. https://doi.org/10.1021/acs.est.6b00830

Kwade, A., Haselrieder, W., Leithoff, R., Modlinger, A., Dietrich, F., & Droeder, K. (2018). Current status and challenges for automotive battery production technologies. *Nature Energy*, *3*(4), 290–300. https://doi.org/10.1038/s41560-018-0130-3

Le Varlet, T., Schmidt, O., Gambhir, A., Few, S., & Staffell, I. (2020). Comparative life cycle assessment of lithium-ion battery chemistries for residential storage. *Journal of Energy Storage*, *28*(1), 101230. https://doi.org/10.1016/j.est.2020.101230

Liu, N., Ma, Z., & Kang, J. (2017). A regional analysis of carbon intensities of electricity generation in China. *Energy Economics*, *67*, 268–277. https://doi.org/10.1016/j.eneco.2017.08.018

Majeau-Bettez, G., Hawkins, T. R., & Strømman, A. H. (2011). Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. *Environmental Science & Technology*, *45*(10), 4548–4554. https://doi.org/10.1021/es103607c

Marques, P., Garcia, R., Kulay, L., & Freire, F. (2019). Comparative life cycle assessment of lithium-ion batteries for electric vehicles addressing capacity fade. *Journal of Cleaner Production*, *229*, 787–794. https://doi.org/10.1016/j.jclepro.2019.05.026

Mauler, L., Duffner, F., & Leker, J. (2021). Economies of scale in battery cell manufacturing: The impact of material and process innovations. *Applied Energy*, *286*, 116499. https://doi.org/10.1016/j.apenergy.2021.116499

Michaelis, S., & Rahimzei, E. (2020). *Roadmap batterieproduktionsmittel 2030: Update 2020*. VDMA. https://battprod.vdma.org/en/viewer/-/v2article/render/59579372

Michaelis, S., & Rahimzei, E. (2018). *Lithium-ion battery cell production process*. Frankfurt am Main. http://elektromobilitaet.vdma.org/viewer/-/v2article/render/26977406

Musk, E. (2020). *Tesla battery day 2020*. Tesla, Inc.

Notter, D. A., Gauch, M., Widmer, R., Wäger, P., Stamp, A., Zah, R., & Althaus, H. -J. (2010). Contribution of Li-ion batteries to the environmental impact of electric vehicles. *Environmental Science & Technology*, *44*(17), 6550–6556. https://doi.org/10.1021/es903729a

O'Sullivan, A., Cooper, K. H., & Sheffrin, S. M. (2002). *Economics: Principles in action*. Pearson Prentice Hall.

PEM of RWTH Aachen. (2017). *Trockenraum in der Batterieproduktion neu gedacht*. https://www.pem.rwth-aachen.de/go/id/mriw

Redl, C., Hein, F., Buck, M., Graichen, P., & Jones, D. (2021). The European Power Sector in 2020: Up-to-Date Analysis on the Electricity Transition. https://static.agora-energiewende.de/fileadmin/Projekte/2021/2020_01_EU-Annual-Review_2020/A-EW_202_Report_European-Power-Sector-2020.pdf

Reißmann, D., Thrän, D., Blöhse, D., & Bezama, A. (2021). Hydrothermal carbonization for sludge disposal in Germany: A comparative assessment for industrial-scale scenarios in 2030. *Journal of Industrial Ecology*, *25*(3), 720–734. https://doi.org/10.1111/jiec.13073

Reuters. (2021). *VW to end sales of combustion engines in Europe by 2035*. https://www.reuters.com/business/sustainable-business/vw-end-sales-combustion-engines-europe-by-2035-2021-06-26/

Romare, M., & Dahllöf, L. (2017). The life cycle energy consumption and greenhouse gas emissions from lithium-ion batteries: A study with focus on current technology and batteries for light-duty vehicles (No. C 243). https://www.energimyndigheten.se/globalassets/forskning--innovation/transporter/c243-the-life-cycle-energy-consumption-and-co2-emissions-from-lithium-ion-batteries-.pdf

Roskill. (2021). Lithium-ion batteries, outlook to 2030.

Schlich, E., & Fleissner, U. (2005). The ecology of scale: Assessment of regional energy turnover and comparison with global food (5 pp). *The International Journal of Life Cycle Assessment*, *10*(3), 219–223. https://doi.org/10.1065/lca2004.09.180.9

Simon, B., & Weil, M. (2013). Analysis of materials and energy flows of different lithium ion traction batteries. *Revue De Métallurgie*, *110*(1), 65–76. https://doi.org/10.1051/metal/2013056

Stewart, R. D., Wyskida, R. M., & Johannes, J. D. (Eds.) (1995). *Cost estimator's reference manual* (2nd ed.). Wiley. http://www.loc.gov/catdir/bios/wiley044/94023415.html

Sun, X., Luo, X., Zhang, Z., Meng, F., & Yang, J. (2020). Life cycle assessment of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles. *Journal of Cleaner Production*, *273*, 123006. https://doi.org/10.1016/j.jclepro.2020.123006

Whattoff, P., Lindsay, J., Pell, R., Paes, C., Alex, G., & Tijsseling, L. (2021). Shifting the lens: The growing importance of life cycle impact data in the battery material supply chain. https://www.minviro.com/wp-content/uploads/2021/10/Shifting-the-lens.pdf

World Economic Forum. (2019). A vision for a sustainable battery value chain in 2030: Unlocking the full potential to power sustainable development and climate change mitigation. Insight Report. World Economic Forum. http://www3.weforum.org/docs/WEF_A_Vision_for_a_Sustainable_Battery_Value_Chain_in_2030_Report.pdf

Yano Research Institute. (2020). *2019–2020: Current status and future prospects of LiB material market, major four components*. https://www.yanoresearch.com/market_reports/C62107020?class_english_code=6

Zackrisson, M., Avellán, L., & Orlenius, J. (2010). Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles – Critical issues. *Journal of Cleaner Production*, *18*(15), 1519–1529. https://doi.org/10.1016/j.jclepro.2010.06.004

Zhao, S., & You, F. (2019). Comparative life-cycle assessment of Li-ion batteries through process-based and integrated hybrid approaches. *ACS Sustainable Chemistry & Engineering*, *7*(5), 5082–5094. https://doi.org/10.1021/acssuschemeng.8b05902

Zhou, Y., Gohlke, D., Rush, L., Kelly, J., & Dai, Q. (2021). *Lithium-ion battery supply chain for e-drive vehicles in the United States: 2010–2020 (ANL/ESD-21/3)*. https://publications.anl.gov/anlpubs/2021/04/167369.pdf

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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