# Energy consumption of current and future production of lithium-ion and post lithium-ion battery cells

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Due to the rapidly increasing demand for electric vehicles, the need for battery cells is also increasing considerably. However, the production of battery cells requires enormous amounts of energy, which is expensive and produces greenhouse gas emissions. Here, by combining data from literature and from own research, we analyse how much energy lithium-ion battery (LIB) and post lithium-ion battery (PLIB) cell production requires on cell and macro-economic levels, currently and in the future (until 2040). On the cell level, we find that PLIB cells require less energy than LIB cells per produced cell energy. On the macro-economic level, we find that the energy consumption for the global production of LIB and PLIB cells will be 130,000 GWh if no measures are taken. Yet, it is possible to optimize future production and save up to 66% of this energy demand.

Global warming is a serious threat to our society[1]. Thus, policymakers are increasingly addressing environmental and social sustainability. In Europe, the European Commission plans to reduce greenhouse gas (GHG) emissions substantially by 2030 (ref. 2) and to be GHG emission neutral by 2050 (ref. 3). A major enabler for achieving this goal is the transition from cars with internal combustion engines to electric vehicles[4]. Many global car companies already have declared that they will no longer produce internal combustion engine cars in the mid-term[5,6]. As a result, the demand for battery cells is increasing markedly. The World Economic Forum predicted that the global battery demand will be 2,600 GWh in 2030 (ref. 7). Figure 1 shows the expected global battery demand from 2021 to 2040 (refs. 7–13) for different Shared Socioeconomic Pathway (SSP) scenarios, as well as the forecasted market shares of different battery chemistries[14].

The SSP is a framework of possible narratives for possible the future of humanity until the year 2100 (ref. 15). Five different possible futures of humanity are described, that is, sustainability (SSP1), middle of the road (SSP2), regional rivalry (SSP3), inequality (SSP4) and fossil fuel (SSP5)[15]. For the future demand for batteries, scenarios SSP1, SSP2 and SSP5 are the most important[10].

Figure 1 shows that, in the SSP2 scenario (middle way), the global demand for battery cells will reach approximately 5,500 GWh in 2040 (refs. 10,12). In the SSP1 (sustainable) scenario, the demand for battery cells could reach 10,000 GWh in 2040, and in the SSP5 scenario (fossil-fuelled), battery cell demand will reach only approximately 2,900 GWh (refs. 10,12). According to market share forecasts from ref. 14, lithium–iron–phosphate (LFP) battery cells will become more important in the future and nickel–manganese–cobalt (NMC) battery cells with high nickel content will have a notable market share in 2040 (ref. 14). Furthermore, the market share of new types of battery cells, respectively post lithium-ion battery (PLIB) cells, will become important in 2030 and reach a market share of approximately 39% in 2040 (ref. 14), still what types of PLIB cells are meant is not specified. However, Xu et al. suggested further possible future market share scenarios for 2040, such as a >95% NCX (X stands for any suitable element) market share scenario, a 60% LFP market share scenario and a 60% PLIB market share scenario[16]. Therefore, the market shares shown in Fig. 1, which are based on ref. 14, are a mix of different, more extreme scenarios of ref. 16.

Currently, lithium-ion batteries (LIBs) are the state-of-the-art battery cell type[16] owing to their high energy density (up to 750 Wh l⁻¹) and

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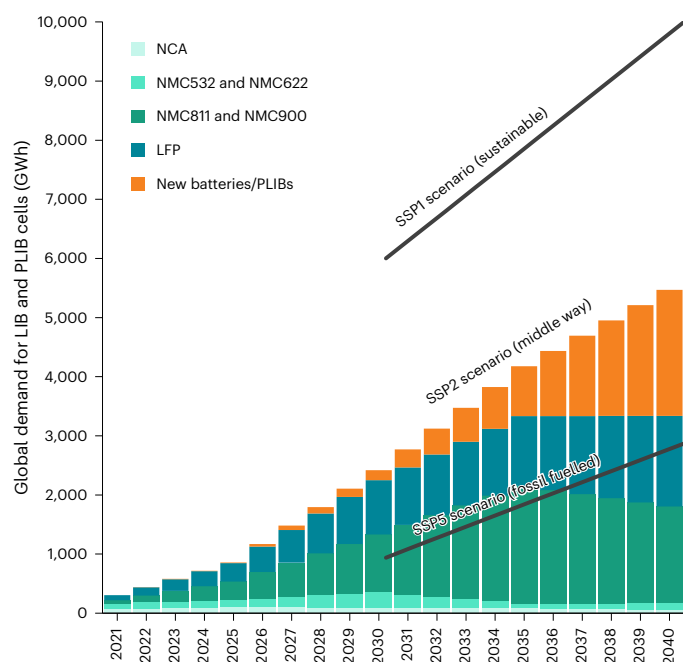
**Fig. 1 | Development of the global demand for LIB and PLIB cells.** The numbers are based on market demand forecasts for 2021–2030 (refs. 7–9,11,13) and 2030–2040 (refs. 10,12) combined with a forecast of market share of cathode chemistries[14]. All market data and calculations can be found in Source Data Fig. 1. NCA, nickel–cobalt–aluminium.

long cycle life (1,000–6,000 cycles), despite several controversially discussed disadvantages[17,18]. To overcome these disadvantages, current cell research and development are focused on increasing energy density while decreasing cost, environmental footprint and safety concerns. Thus, cathode development trends lean towards higher nickel contents, such as NMC900, to improve the energy density[19,20], while anode development trends lean towards higher shares of Si and SiO (refs. 21,22). To foster sustainability and safety as well as reduce cost, development trends are moving towards LFP cells because they do not require the use of cost-intensive nickel and cobalt[23,24].

To further improve battery cells, new types of battery cells, such as PLIB cells, are being developed. One group of PLIB cells is metal-ion battery cells, in which lithium is replaced by, for example, sodium, magnesium, aluminium or zinc[25]. Another group of PLIB cells uses lithium metal on the anode side instead of graphite or silicon or silicon/graphite. Some examples include solid state battery (SSB) cells with a sulfidic, oxidic or polymer-based solid electrolyte (SE). Other PLIB cells with lithium metal are lithium/sulfur battery (LSB) and lithium oxygen/air battery (LAB) cells. Within these cell chemistry classes, a wide range of various PLIB types are possible.

The types of PLIB cells that will reach industrial-scale production currently are unknown. Bhandari et al. forecasted three major technology steps[14]: first, PLIB cell generation will have lithium metal on the anode side combined with state-of-the-art cathode materials in an SE. According to Schmaltz et al., polymer-based SSBs will be commercially available first, and they will be followed by oxidic SSBs and then sulfidic SSBs[12]. The second step involves PLIB cell generation LSB cells, and the third step involves the generation of PLIB LAB cells[26,27]. In addition, it has been predicted that sodium ion battery (SIB) cells will be commercialized within the next few years[18,28]. Other PLIB types are in development, but they are not yet considered in most mid-term battery forecasts[29]. For example, for aluminium-ion, aluminium/air and zinc/air batteries, several challenges must be overcome[30]. Thus, improved LIB cells as well as SIB, SSB, LSB and LAB cells are believed today to be the types of battery cells with the highest commercialization potential in the mid-term[16,18,26,27,29].

To produce today's LIB cells, calculations of energy consumption for production exist, but they vary extensively. Studies name a range of 30–55 kWh_prod per kWh_cell of battery cell when considering only the factory production and excluding the material mining and refining[31–33]. A comprehensive comparison of existing and future cell chemistries is currently lacking in the literature. Consequently, how energy consumption of battery cell production will develop, especially after 2030, but currently it is still unknown how this can be decreased by improving the cell chemistries and the production process. This is essential, as energy is a valuable resource and probably will continue to be for the foreseeable future.

In this Analysis, our aim is to determine how much energy is required for the current and future production of LIB and PLIB cells on a battery cell level and on a macro-economic level. Material mining and refining were excluded from this study due to their complexity.

The analysis was conducted as follows: First, it was determined how the energy consumption in production would change relatively if PLIB cells were produced instead of LIB cells. Then it was calculated how much energy is needed to produce 1 kWh_cell of cell energy according to the current state of the art. Subsequently, it was analysed how techno-economic effects will affect future energy consumption. On this basis, it was then calculated how much energy is needed to produce 1 kWh_cell of cell energy in the future. Finally, it was calculated how much energy is needed to produce the worldwide demand for batteries from today until 2040.
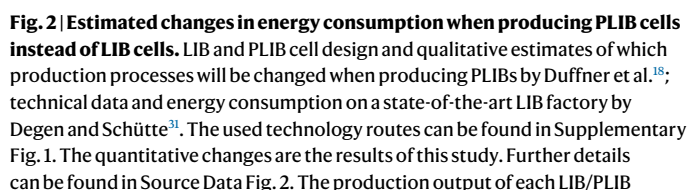
## Energy consumption changes to produce PLIB cells

In the first step, we analysed how the energy consumption of a current battery cell production changes when PLIB cells are produced instead of LIB cells. As a reference, an existing LIB factory model was used[31,34], which is provided in Supplementary Fig. 1 and Supplementary Table 1. How future PLIB production technology routes might look and which technology routes we used as references in this study are shown in Supplementary Fig. 2. However, to be able to quantify the percentage of the change in energy consumption between LIB and PLIB cell production, we conducted workshops in which experts rated each single production step. Details about this work are provided in Methods and in Supplementary Note 1. The results that were obtained are shown in Fig. 2.

## Energy consumption for today's production on cell level

Based on the numbers in Fig. 2, the energy consumption of PLIB cell production is calculated. Figure 3 shows the energy consumption for each production step of all relevant LIB[14] and PLIB cells likely to be commercially relevant from now until 2040 (ref. 26). The energy necessary to produce 1 kWh_cell of cell energy for nickel-cathode-based LIB cells ranges between 20 kWh_prod and 29 kWh_prod. The energy consumption of LIB cell production decreases as the energy density increases. NMC900 cells with carbon-based and silicon anodes have the lowest energy demand in LIB cell production, with approximately 20.3 kWh_prod. Notably, LFP cells, with 37.5 kWh_prod, have the highest production energy demand of all of the battery cells that were analysed. Furthermore, in LIB cell production today, the largest amount of energy is consumed by the three production steps of coating, drying and formation, with the dry rooms being the largest energy consumer.

Regarding PLIB cells, Fig. 3 shows that SIB cells are likely to have an energy demand of 23.0 kWh_prod, based on today's production technology and know-how for LIB production. This is on a level that is similar to current NMC811 cells. SSB energy consumption in production varies depending on the SE that is used because this notably affects the required production infrastructure[18]. Polymer-based SSBs have the lowest energy demand (10.6 kWh_prod), followed by oxidic SSBs (11.8 kWh_prod), and sulfidic SSBs have the highest energy demand

**Fig. 2 | Estimated changes in energy consumption when producing PLIB cells instead of LIB cells.** LIB and PLIB cell design and qualitative estimates of which production processes will be changed when producing PLIBs by Duffner et al.[18]; technical data and energy consumption on a state-of-the-art LIB factory by Degen and Schütte[31]. The used technology routes can be found in Supplementary Fig. 1. The quantitative changes are the results of this study. Further details can be found in Source Data Fig. 2. The production output of each LIB/PLIB production step is assumed to be constant. Reliability refers to only new/changed processes. Note: to achieve a constant dew point of $T_{dp} = -40\,°C$, the air supply has to have a dew point of $T_{dp} = -60\,°C$ ($T_{dp} = 70\,°C$ air supply for a constant dew point of $T_{dp} = -60\,°C$). EOL, end of line; OCV, open circuit voltage; $T_{dp}$, dew point temperature; Wel., welding; Pac., packaging; Fil., electrolyte filling; Clo., closing; cont., continuous; Form., formation; Infras., infrastucture.

($17.5\,kWh_{prod}$). Based on today's production technology, LSB cells will require $13.4\,kWh_{prod}$ and LAB cells will require $20.9\,kWh_{prod}$. However, these results are affected by the different areal energy density ($kWh_{prod}$ per $m^2_{cell}$) of the analysed cell chemistry. The material flow of a battery cell factory is assumed to be constant (in particular $m^2$ of produced and processed electrodes), and Fig. 4 shows how much energy is required per area of electrode material produced and processed (in $kWh_{prod}$ per $m^2_{cell}$).

Figure 4 shows that all LIB cells and SIB cells have the same average energy consumption of $5.2\,kWh_{prod}$ per $m^2_{cell}$ in production. That means that, for LIB and SIB cells, the different energy consumption per produced cell energy ($kWh_{prod}$ per $kWh_{cell}$) from Fig. 3 results solely from the different areal energy densities ($kWh_{cell}$ per $m^2_{cell}$) of the cell chemistries. However, PLIB cells also show different energy consumptions per material throughput from those of LIB and SIB cells due to their different production infrastructure. For SSB cells, the energy consumption per produced and processed electrode area ($kWh_{prod}$ per $m^2_{cell}$) is higher than it is for LIB cells. But due to the higher areal energy densities ($kWh_{cell}$ per $m^2_{cell}$) of the SSB cells compared with the LIB cells, lower energy consumption per produced cell energy ($kWh_{prod}$ per $kWh_{cell}$) is the result. For LSB and LAB cells, the opposite is true, that is, notably less energy is required per produced and processed electrode area, but due to the lower areal energy densities of the LSB and LAB cells, their energy consumption per produced cell energy ($kWh_{prod}$ per $kWh_{cell}$) is comparable to LIB cells.

## Techno-economic effects on future's energy consumption

There are natural uncertainties in any market forecasts and energy modelling, which so far have not been considered. In addition, it can be assumed that the production of battery cells will be improved in the future through new technologies. Therefore, in this analysis, we calculated the impact of new production and material technologies on the future energy consumption of production as shown in Table 1. In particular, we selected those technologies that have notable impacts on the main energy consumers in the production of battery cells, for
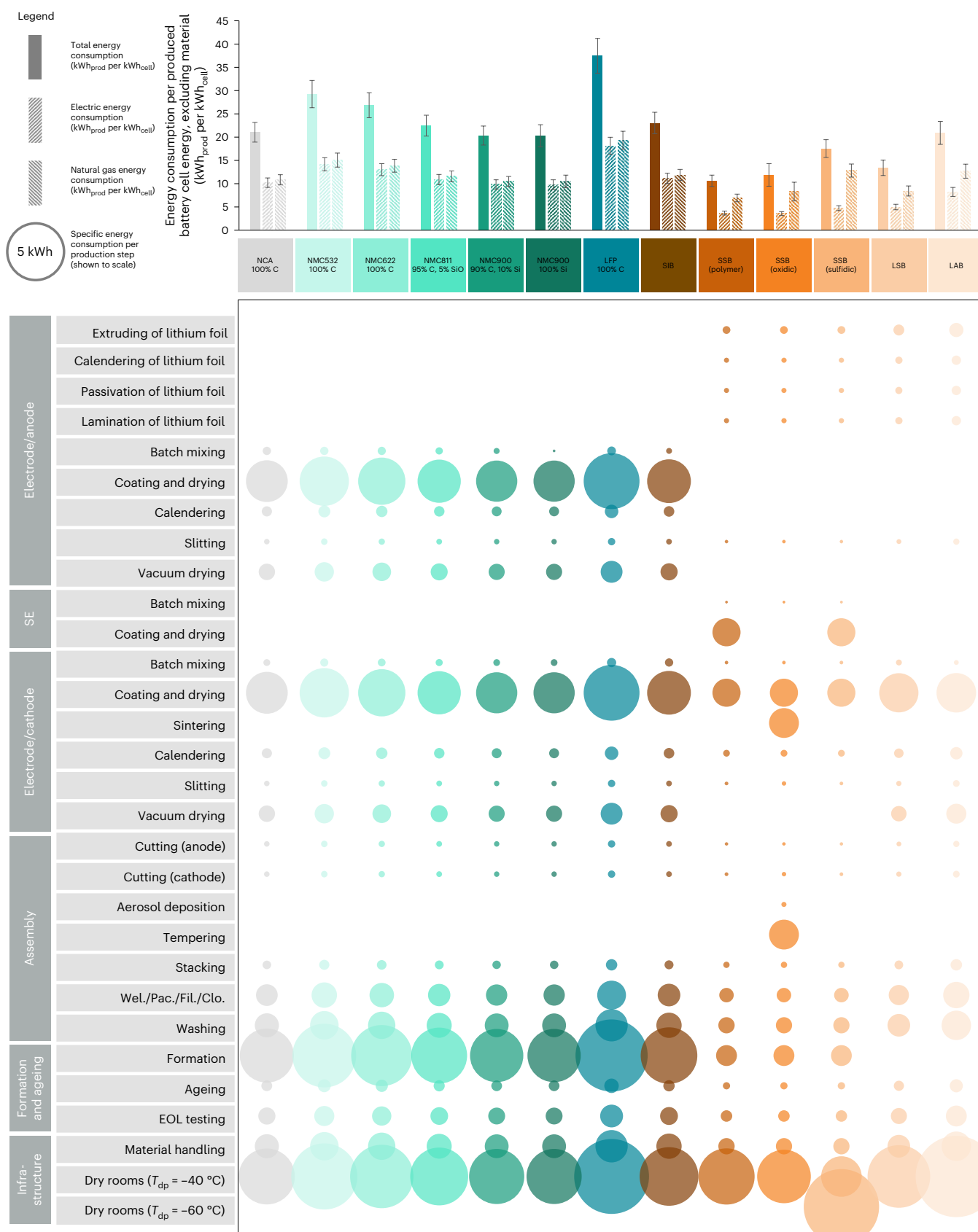
**Fig. 3 | Calculated energy consumption (kWh_prod) for LIB and PLIB cell production per produced kWh_cell of cell energy with today's production technology.** The different sizes of the circles represent the different sums of energy (kWh_prod) of electricity and natural gas. Detailed numbers can be found in Source Data Fig. 3. The main bars show the calculated mean value. The error bars show the s.d. resulting from the uncertainties in the expert assessments. Sixty experts were interviewed ($n = 60$). Any battery materials are excluded from the assessment. EOL, end of line; $T_{dp}$, dew point temperature. Wel., welding; Pac., packaging; Fil., electrolyte filling; Clo., closing.
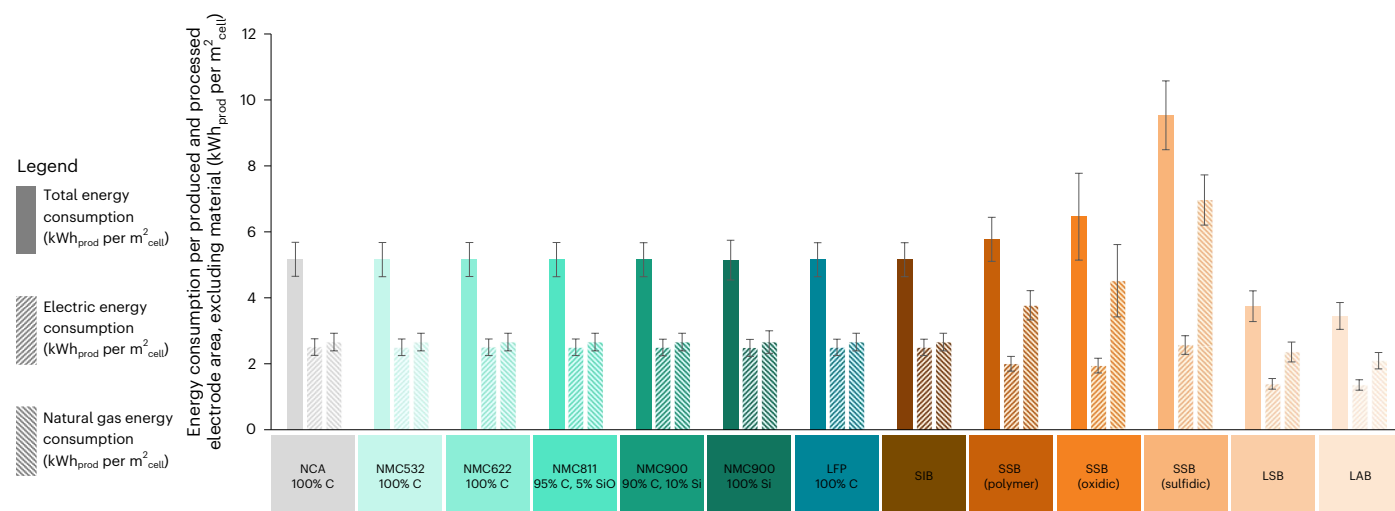
**Fig. 4 | Calculated energy consumption for LIB and PLIB cell production ($kWh_{prod}$) per produced and processed electrode area ($m^2_{cell}$) of a battery cell factory.** Detailed numbers can be found in Source Data Fig. 4. The main bars show the calculated mean value. The error bars show the s.d. resulting from the uncertainties in the expert assessments. Sixty experts were interviewed ($n = 60$).

example, drying, dry room, formation and sintering/tempering and might be industrialized and used extensively by 2040. The calculations for this are available in Source Data Table 1. Further information can be found in Supplementary Note 2. It has been shown that when new technologies are fully (100%) industrialized and applied by 2040, between 42.5% and 57.0% savings in energy consumption per produced and processed electrode area can be achieved. This corresponds to an annual saving of 3.0–4.3%, depending on the cell chemistry.

In addition to the further development of production and material technologies, there are other techno-economic effects that can reduce energy consumption in production, such as the use of heat pumps, learning effects and economies of scale[35]. How these improvements can affect global energy consumption in the production of battery cells in 2040 is shown in Fig. 5. Figure 5 also shows how uncertainties in market growth, market distribution and energy demand modelling can affect global energy consumption in battery cell production in 2040. Figure 5 shows that the largest future uncertainties are market growth and the market distribution of future cell chemistries. It also shows that the largest energy savings are possible through new technologies (31–52%) and the use of heat pumps (11–20%). Learning effects (14–26%) and economies of scale (8–16%) also are relevant, but they are less important.

## Energy consumption for future's production on cell level

How these improvements affect the energy consumption of the production of a single LIB or PLIB cell until 2040 is shown in Fig. 6. Due to technology improvements, use of heat pumps, learning effects and economies of scale for the production of LIB and PLIB cells, the energy demand will be notably lower in 2040 than with today's production technology and know-how. For instance, to produce an LFP cell today, $37.5 \, kWh_{prod}$ per $kWh_{cell}$ is necessary; in 2040, only $12.9 \, kWh_{prod}$ per $kWh_{cell}$ will be necessary. However, due to the uncertainties associated with future developments, a wide range between 8.2 and 20.1 $kWh_{prod}$ per $kWh_{cell}$ is possible for LFP cells. Nevertheless, for all analysed LIB and PLIB cells, a reduction of energy consumption for production of 62–71% is forecasted, depending on the cell chemistry.

## Energy consumption on macro-economic level

Figure 7 shows how energy demand for global production of LIB and PLIB cells probably will develop from today to 2040 in the SSP2 (middle way) scenario. This is done for a mixed, an LFP, an NMX and a PLIB market share scenario. Techno-economic effects, such as technology improvements, the use of heat pumps, learning effects and economies of scale, are considered now. In addition, uncertainties regarding these effects and energy modelling are examined and illustrated by error bars. As a reference, the energy demand forecast is illustrated on the basis of today's technology level.

Figure 7 shows that, based on the analysed techno-economic effects, the energy consumption of LIB and PLIB cell production will be notably lower than when extrapolating today's energy demands in LIB and PLIB cell production to future market demands and shares. According to our calculations, for a mixed scenario in 2040, instead of approximately 130,000 $GWh_{prod}$ (today's technology extrapolated to the future), 44,600 $GWh_{prod}$ will be necessary for LIB and PLIB cell production per year, excluding material. This is a decrease of 85,400 $GWh_{prod}$ per year or 66% due to the improvement of production.

Figure 7 also shows that in a possible future scenario where PLIBs have even higher market shares, for example, in 2040, only 33,800 $GWh_{prod}$ per year will be necessary for global cell production, which is a further decrease of 10,800 $GWh_{prod}$ compared with the mixed scenario. However, in a mixed scenario, we identified a peak in 2031, where energy demand in LIB and PLIB cell production stops increasing, although the global battery demand is still growing. Afterwards, according to our calculations, even a minor decrease in energy consumption for global LIB and PLIB cell production is possible in the future.

However, Fig. 7 also shows that PLIB cells favour low energy demands in global production, while LFP cells disfavour these. In an NMX scenario the future energy demand is similar to the mixed scenario, where NMX, LFP and PLIB cells have similar market shares in 2040. The GHG emissions resulting from the calculated energy consumption are shown in Supplementary Figs. 4 and 5.

## Discussion

The results show that, by today's production technology and today's know-how, PLIB cell production will require less energy (10.6–23.0 $kWh_{prod}$ per $kWh_{cell}$) than LIB cell production (20.3–37.5 $kWh_{prod}$ per $kWh_{cell}$), when excluding the material from this calculation. We show that these results are affected strongly by the areal energy density of the specific cell chemistry. When relating the energy consumption only to the area of produced and processes electrodes, LIB and SIB cells require

**Table 1 | Analysis of energy savings per produced and processed area of electrodes, due to new production technologies and material technologies**

| New production technology | Affected production step | LIB | SIB | SSB (polymer) | SSB (oxidic) | SSB (sulfidic) | LSB | LAB | Summary of physical effect of technology regarding consumption, compared with the reference process | Assumed electric energy consumption of machine | Assumed thermal energy consumption of machine |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Coating of high-solid slurry | | -7.2% | -7.2% | -6.5% | -2.9% | -3.9% | -5.0% | -3.2% | Less liquid solvent requires less drying, more solid required more mechanical force | +50% | -33% |
| Laser drying | Drying of electrode (reference: convective drying) | -12.3% | -12.3% | -11.1% | -4.9% | -6.7% | -8.5% | -5.5% | Laser drying is more efficient, but laser generation requires more electricity | +566% | -100% |
| Near-infrared (NIR) drying | | -12.3% | -12.3% | -11.1% | -4.9% | -6.7% | -8.5% | -5.5% | NIR drying is more efficient, but NIR beam generation requires more electricity | +566% | -100% |
| Dry coating | | -18.2% | -18.2% | -16.4% | -7.3% | -9.9% | -12.6% | -8.2% | No liquid has to be dried anymore, but material has processed by mechanical force | +310% | -100% |
| Smart dry rooms | | -3.7% | -3.7% | -7.4% | -6.1% | -10.4% | -7.3% | -7.9% | Air is dehumidified only when required | -15% | -15% |
| Macro-environments | Dry rooms (reference: full room with -40°C dew point) | -7.4% | -7.5% | -14.8% | -12.1% | -20.8% | -14.6% | -15.8% | Less air is dehumidified | -30% | -30% |
| Micro-environments | | -16.1% | -16.2% | -32.2% | -26.3% | -45.1% | -31.6% | -34.3% | Much less air is dehumidified | -65% | -65% |
| Water-insensitive electrolytes | | -22.3% | -22.4% | n/a | n/a | n/a | n/a | n/a | No air is dehumidified, but air still has to be cleaned (clean room) and chilled | -90% | -90% |
| Prelithiation | | -2.3% | -2.3% | -0.7% | -0.6% | -0.4% | n/a | n/a | Slightly less energy required for formation and solid electrolyte interphase generation | -10% | |
| High c-rate formation | Formation of cells (reference: 3 cycles at 0.25C) | -5.8% | -5.8% | -1.7% | -1.5% | -1.0% | n/a | n/a | Less cycle and less energy demand, but more heat losses due to higher currents | -25% | |
| Adaptive formation with partial cycles | | -11.5% | -11.6% | -3.4% | -3.1% | -2.1% | n/a | n/a | Less cycle and less energy demand, but more heat losses due to higher currents and controls | -50% | |
| Improved oxidic SE precursor | Sintering and tempering | n/a | n/a | n/a | -7.5% | n/a | n/a | n/a | Instead of 650°C, sintering and tempering takes place at 450°C | -30% | |
| Combination of technologies with highest energy saving potential | | -52.1% | -52.2% | -51.9% | -44.1% | -57.1% | -44.1% | -42.5% | Combination of dry coating, adaptive formation with partial cycles and water-insensitive cell chemistry (LIB and SIB) or micro-environments (SSB, LSB and LAB) | | |
| | | -3.80% | -3.81% | -3.78% | -3.02% | -4.36% | -3.02% | -2.87% | For 100% use of above-mentioned technologies in 2040 | | |
| Average annual savings (2021–2040) | | -2.80% | -2.80% | -2.79% | -2.26% | -3.16% | -2.27% | -2.16% | For 80% use of above-mentioned technologies in 2040 | | |
| | | -1.95% | -1.96% | -1.95% | -1.60% | -2.18% | -1.61% | -1.54% | For 60% use of above-mentioned technologies in 2040 | | |

We selected those technologies that have a notable impact on the main energy consumers in the production of battery cells (drying, dry room, formation and sintering/tempering) and might be industrialized and used extensively by 2040. Detailed numbers can be found in Source Data Table 1. n/a, not applicable.

**Fig. 5 | Analysis regarding decreased energy consumptions due to techno-economic effects and improvements and uncertainties of our assumptions.** We assumed that battery cell production will be improved markedly in the future, so the demand for energy will decrease. The most important effects are technology improvements, use of heat pumps, learning effects and economies of scale[35]. The calculations are in Source Data Fig. 5.
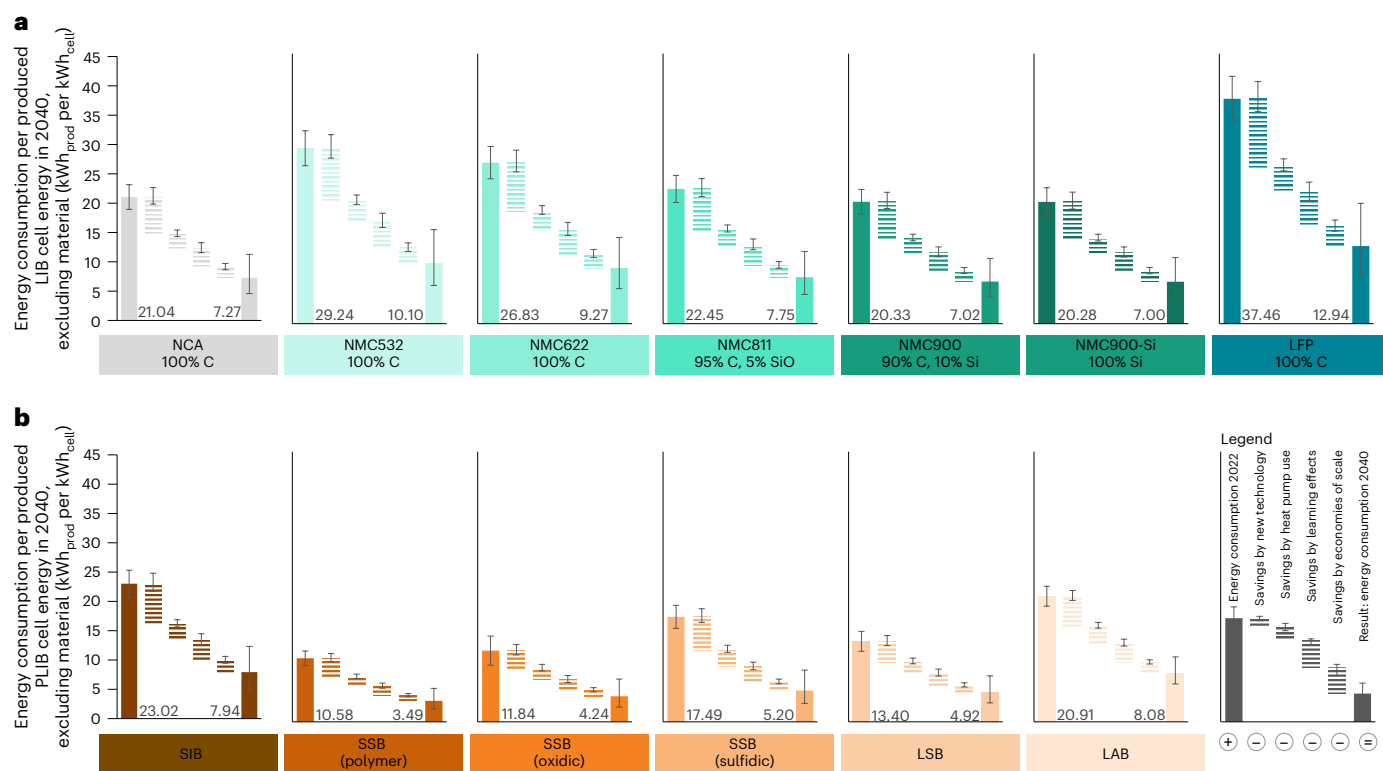


**Fig. 6 | Calculated energy consumption (kWh$_{prod}$) for LIB cell and PLIB cell production per produced kWh$_{cell}$ of cell energy based on today's (2022) technology level and for the technology level of 2040. a,b,** Energy consumption for LIB cell (**a**) and PLIB cell (**b**) production. It is assumed that the current energy consumption will be improved substantially by technology improvements, heat pump use, learning effects and economies of scale. Detailed numbers can be found in Source Data Fig. 6. The main bars show the calculated mean value. The error bars show the s.d. resulting from the uncertainties in the expert assessments. Sixty experts were interviewed ($n = 60$).

5.2 kWh$_{prod}$ per m$^2_{cell}$, SSB cells require 5.8 – 9.6 kWh$_{prod}$ per m$^2_{cell}$, LSB cells 3.7 kWh$_{prod}$ per m$^2_{cell}$ and LAB cells 3.5 kWh$_{prod}$ per m$^2_{cell}$.

However, when considering future developments, by various techno-economic effects, until 2040 a reduction of energy demand between 62% and 70% is possible resulting in 7.0–12.9 kWh$_{prod}$ per kWh$_{cell}$ for LIB cells and 3.5–7.9 kWh$_{prod}$ per kWh$_{cell}$ for analysed PLIB cells. Thus, in a mixed scenario in 2040 a total 44,600 GWh$_{prod}$ (10,932 ktCO$_2$eq GHG emissions) will be necessary for global LIB and PLIB cell production,

instead of 130,000 GWh$_{prod}$ (41,213 ktCO$_2$eq GHG emissions) which are necessary with today's production technology and know-how. By accelerating PLIB cell industrialization and market shares, a further decrease of 10,800 GWh$_{prod}$ to 33,800 GWh$_{prod}$ (8,191 ktCO$_2$eq GHG emissions) per year is possible. In addition, in 2031, the increase in energy consumption for global LIB and PLIB cell production might reach a peak of approximately 44,860 GWh$_{prod}$ and might even decline afterwards, although the battery market will still be growing.
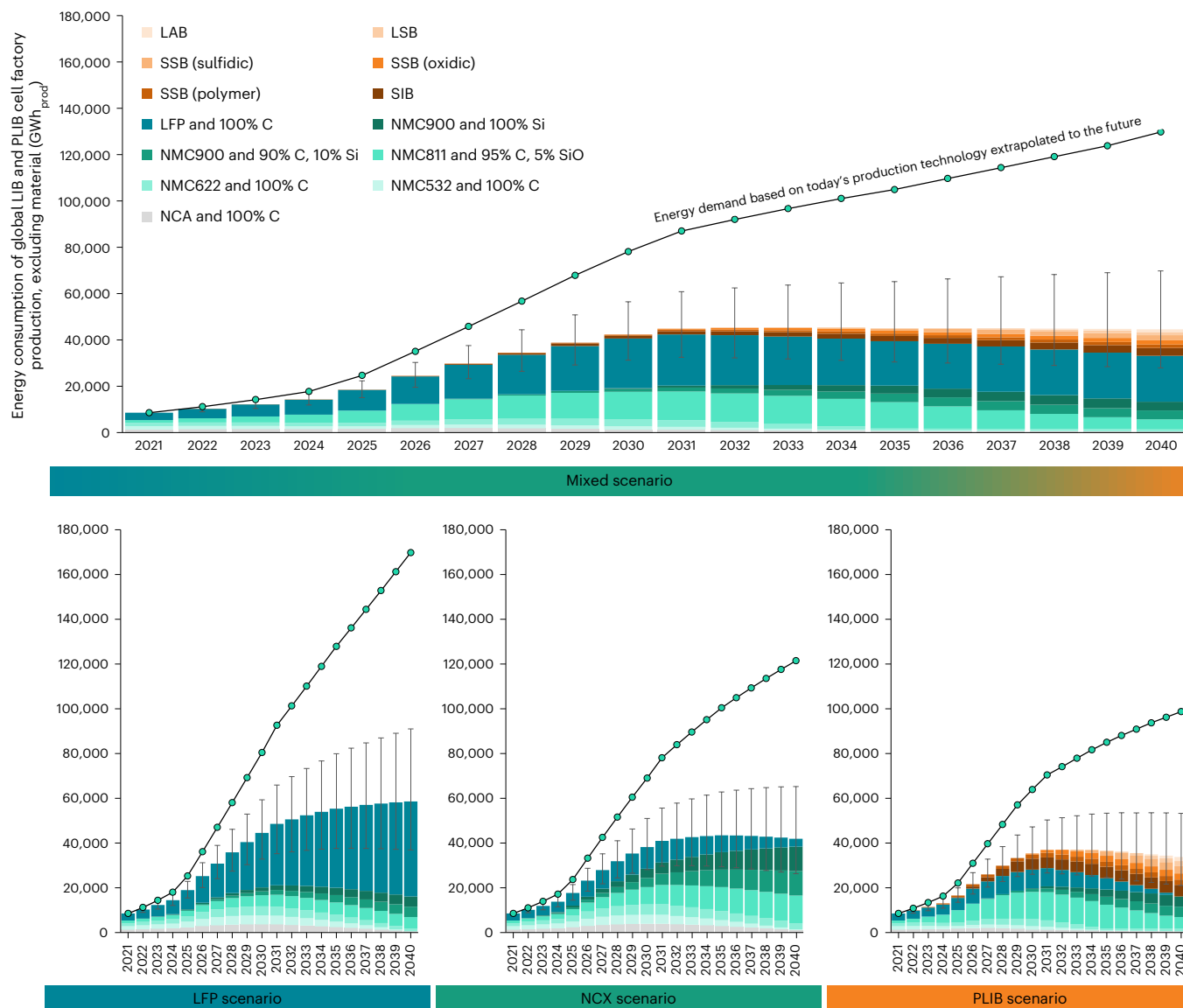
**Fig. 7 | Energy consumption of global LIB and PLIB cell production.** The figure shows the forecast once based on today's technology and know-how level, and once when considering technology improvements, heat pump use and learning effects, as well as economies of scale. This is done for a scenario in which market shares are mixed (based on ref. 14) and for LFP, NCX and PLIB scenarios (based on Xu et al.[16]). Detailed numbers can be found in Source Data Fig. 7. The main bars show the calculated mean value. The error bars show the s.d. resulting from the uncertainties in the expert assessments. Sixty experts were interviewed (n = 60).

These results lead to the following statements based on the analysed cell chemistries in this paper. First, the production infrastructure for SSB cells requires more energy, whereas less energy is required for LSB and LAB cells, both compared with LIB cells. Second, energy consumption for production, related to cell energy ($kWh_{prod}$ per $kWh_{cell}$) is lower for PLIB cells than for LIB cells. Third, due to their low areal energy densities, LFP cells and SIB cells have the highest ratio of $kWh_{prod}$ to $kWh_{cell}$ among the types of cells that were analysed. This is notable since both cell types are discussed as sustainable alternatives to nickel-based LIB cells in particular due to their easier material availability[23,24]. Fourth, owing to large investments in battery production infrastructure, research and development, the resulting technology improvements and techno-economic effects promise a reduction in energy consumption per produced cell energy by two-thirds until 2040, compared with the present technology and know-how level. Fifth, on a global level, the energy consumption in 2040 for battery cell production will be 130,000 $GWh_{prod}$, with today's technology and know-how

level, which is equal to the annual electric energy demand of Norway or Sweden (in 2021)[36]. Sixth, it is possible to improve the production of battery cells so that, in 2040, 85,400 $GWh_{prod}$ could be saved per year (−66%), which is the electric energy demand of Belgium or Finland (in 2021)[36]. Seventh, by improving the areal energy density, for example, by accelerating the industrialization of PLIB cells and increasing its market shares, in 2040 an additional 10,800 $GWh_{prod}$ for global battery cell production could be saved per year. Eighth, through the analysed improvements, it is likely that, in 2031, energy consumption for LIB and PLIB cell global will reach a peak and might even decline afterwards, despite the additional growth of the market.

The results discussed above lead to the following implications in terms of energy consumption in cell production. First, a high areal energy density of the specific cell chemistry is key for a low ratio of $kWh_{prod}$ to $kWh_{cell}$, at least for production. This can be achieved by SSB cells but also by further developed LIB cells with their high nickel contents. Second, when it comes to energy consumption for production,

LFP and SIB cells might not be as sustainable as often advertised. LIB and SIB cells should be questioned as sustainable cells. Third, improvements in production-related technology matters substantially, not just for PLIB cells but also, or even especially, for LIB cells. Therefore, resources should be invested not only in cell development, but also in the development of production technology. Fourth, by a combination of the measures mentioned above, the increase in energy demand for global LIB and PLIB production can be reduced or even stopped. This is vital for a reduction of battery production related GHG emissions and to reduce global warming.

Besides production, material accounts for a high share of energy consumption in the life cycles of batteries[37]. Because materials and their production were excluded from this study, and also their mining and refining is very energy consuming (50–70% of total energy consumption)[38,39], in future studies, it is very important to extend our research with values from material mining, the use phase, and the recycling of battery cells. This is highly recommended for LFP and SIB cell chemistries to validate how sustainable they are in terms of energy consumption. Furthermore, we recommend that LIB cell technology and its production be optimized. Both LIBs and PLIBs will have the opportunity to be relevant types of battery cells and will be vitally important for reducing energy consumption in 2040.

## Methods

### Energy consumption changes to produce PLIB cells

First, we analysed how electrical and natural gas power ($P$) of production machines will change, when producing PLIB parts instead of LIB parts at a constant material flow rate ($Q$). For this, an adjustment parameter $\lambda_j$ is defined as

$$\lambda_j = \frac{\text{increase } (+)}{\text{decrease } (-)} \text{ change of machine power } (\%) + 1. \tag{1}$$

$\lambda_j$ is obtained once for electrical power and once for natural gas power. To obtain $\lambda_j$, 60 battery cell experts evaluated in workshops the quantitative impact of the changed production infrastructure on required machine power. The workshops were conducted in two phases, with the experts split into two groups: first phase—calculating the relative changes in energy consumption from LIB to PLIB production only for the single defined production step/machine (expert group 1); second phase—reviewing and adapting the results from phase 1 in the context of all obtained results (expert group 2).

Each workshop in the first phase followed the same structure: first, investigating the energy consumption for today's LIB production; second, identifying the main energy consumers and thermomechanical effects that cause the largest energy consumption; third, identifying how requirements for the machine are changed when producing PLIB components instead of LIB components; fourth, identifying what technical changes in the machine are necessary to be able to process PLIB components; fifth, estimating what these changes to the machine mean in terms of energy consumption; sixth, estimating how reliable the assumptions are.

In the second phase workshops, the results were presented to the second group of experts, who had to review the previous, process-specific assumptions from expert group 1 in the context of all other results. The structure was as follows: first, giving an overview of the obtained results; second, explaining the calculations of expert group one; third, identifying similar production processes compared with the process that is in focus (reference process); fourth, comparing the calculations between the focus process and the reference process; fifth, questioning the estimations/calculations made by the expert group one; sixth, adapting the calculations from first phase if necessary; seventh, estimating how reliable the made calculations are.

A total of 60 experts were questioned, 30 in phase 1 and 30 in phase 2. Each workshop consisted of one to three experts. Each workshop

took approximately 1 h on average. In total, 26 workshops were conducted. Each expert was asked how reliable they think their made estimations are. The experts could choose between lower, medium, and higher reliability. They also were asked why they made their choice. The following risk factors, $\eta_j$, are defined: high reliability ($\eta_j = 0.1$), medium reliability ($\eta_j = 0.2$), low reliability ($\eta_j = 0.5$).

### Energy consumption for today's production on cell level

For this study, an LIB factory model of Degen and Schütte was used, which provides energy consumption of each production machine as well as the machining parameter[31]. An extended version of the model was given by Degen and Krätzig[34]. Following relevant parameters are used: The electrical power of production machine ($P_{j,\text{electric}}$), the natural gas power of production machine ($P_{j,\text{gas}}$), the produceable material flow rate ($Q_{j,\text{cell}}$) for each specific process step ($j$). By the data from the factory model, it is possible to calculate the energy consumption per material flow that is produced ($E_{j,\text{electric}}, E_{j,\text{gas}}$):

$$E_j = \frac{P_j}{Q_{j,\text{cell}}} \text{ in } \left[\text{kWh}_{\text{prod}} \text{ per m}^2_{\text{cell}}\right]. \tag{2}$$

This, in combination with the cell chemistry specific areal electrode stack energy content ($\text{kWh}_{\text{cell}}$ per $\text{m}^2_{\text{cell}}$), makes it possible to calculate the ratio of $\text{kWh}_{\text{prod}}$ to $\text{kWh}_{\text{cell}}$ ratio, $i_{j,\text{energy}}$, for each production step:

$$i_{j,\text{energy}} = \frac{(E_{j,\text{electric}} + E_{j,\text{gas}})}{\text{Areal energy content}} \text{ in } \left[\text{kWh}_{\text{prod}} \text{ per kWh}_{\text{cell}}\right]. \tag{3}$$

The overall $i_{\text{energy}}$, existing for each cell chemistry, is the sum of all production processes within the value chain:

$$i_{\text{energy}} = \sum_{i=\text{mixing}}^{\text{EOL testing}} i_{j,\text{energy}}. \tag{4}$$

Bottleneck of our used factory model is the assembly line with:

$$Q_{\text{assembly,cell}} = 840 \text{ m}^2 \text{ min}^{-1}. \tag{5}$$

This is equal to 200 cylindrical cells or 50 pouch cells per minute. Thus, all other production steps are adapted to this lead material flow rate, either by reducing the production speed or by not using the machine. A linear relationship is assumed between the required machine power and the produced material flow.

The power of the production machines for PLIB cell production is then calculated as follows:

$$P_j^{\text{PLIB}} = \lambda_j \times P_j^{\text{LIB}}. \tag{6}$$

$$P_j^{\text{PLIB}}(\text{max}) = \lambda_j \times P_j^{\text{LIB}} \times (1 + \eta_j). \tag{7}$$

$$P_j^{\text{PLIB}}(\text{min}) = \lambda_j \times P_j^{\text{LIB}} \times (1 - \eta_j). \tag{8}$$

### Techno-economic effects on future's energy consumption

To calculate the energy consumption required to produce a single LIB and a single PLIB cell with 1 $\text{kWh}_{\text{cell}}$ of cell energy, in addition to the battery cell type, four techno-economic effects were addressed: technology improvements[29,35,40–43], use of heat pumps[31,44], learning effects[35,43,45] and economies of scale[43,46,47]. The made assumptions can be found in Supplementary Table 2.

**Technology improvements.** To estimate how technological developments may affect future energy consumption in cell production, first

the main energy consumers in cell production were analysed. These are coating and drying, dry rooms, formation, and sintering and tempering (of oxidic SSB cells). Then, the process experts gathered in workshops and discussed the existing alternative technologies, the new technologies that were in development, and which of the technologies might have notable impacts on the energy consumption of the LIB cells, and PLIB cell production. Afterwards, for each of the gathered technologies, it was estimated how electrical and natural gas power ($P$) of production machines will change when changing the production process. The material flow rate ($Q$) is kept constant. For this a technology adjustment parameter $\varepsilon_j$ is defined, once for electric energy ($\varepsilon_{j,\text{electric}}$) and once for natural gas ($\varepsilon_{j,\text{gas}}$), which is calculated by

$$\varepsilon_j = \frac{\text{increase}\,(+)}{\text{decrease}\,(-)} \text{ change of machine power }(\%) + 1. \tag{9}$$

By that, the machine power can be calculated as follows:

$$P_j^{\text{new}} = \varepsilon_j \times P_j^{\text{reference}}. \tag{9}$$

By the new obtained $P_j^{\text{new}}$, it is possible to calculate $E_j^{\text{new}}$:

$$E_j^{\text{new}} = \frac{P_j^{\text{new}}}{Q_{j,\text{cell}}} \text{ in }\left[\text{kWh}_{\text{prod}} \text{ per m}^2_{\text{cell}}\right], \tag{10}$$

and then

$$E^{\text{new}} = \sum_{i=\text{mixing}}^{\text{EOL Etesting}} E_j^{\text{new}} \text{ in }\left[\text{kWh}_{\text{prod}} \text{ per m}^2_{\text{cell}}\right]. \tag{11}$$

Then the energy saving potential can be calculated as shown below:

$$s = \frac{E^{\text{new}}}{E^{\text{reference}}} - 1. \tag{12}$$

This is for the case that the reference technology is completely (100%) substituted by the new technology. According to the expert workshops, it might be unlikely that until 2040 all analysed technologies will be fully industrialized and have a market share of 100%. Thus, we assume this to be the maximum scenario (large effect). We assume lower market shares of 80% in a trend scenario (medium effect) and 60% in a minimum scenario (small effect).

The results that were obtained were compared afterwards with the results from the literature; in particular, the studies of von Drachenfels et al., Mauler et al. and Degen were used[29,35,40]. The studies analysed the impact of technology improvements on cost[29] and on the energy consumption the production of battery cells[35,40]. For example, an energy reduction of 2–3% per year was reported for an NMC622 cell with high power configuration (41 µm thickness of cathode active material)[35]. Thus, our results are in the same range as the literature results.

**Use of heat pumps.** For improved energy sourcing, it is assumed that electricity is used instead of natural gas and that heat pumps are used for the generation of heat. For the calculations of the use of heat pumps, a coefficient of performance (COP) between 1.5 and 2.5 was used for temperatures above 100 °C (ref. 44). We assumed that 60% of the factories will be equipped with heat pumps in 2040.

**Learning effects.** Learning effects result from experience in production, such as reducing scrap rates and using machines and tools more efficiently. It is described by a percentual cost reduction by doubling the cumulated production output. According to the National Aeronautics and Space Administration, learning effects in the field of 'repetitive electronics manufacturing' are 5% for cost[45]. We assumed a reduction

of energy consumption of 3–5% by doubling the cumulative production output[35].

**Economies of scale.** By economies of scale, the effect is described that the effort (cost) to produce a product is reduced with increased scale in its production. This is achieved by synergy effects and by fixed cost degression. The effect of economies of scale does not affect only the economic cost, but it also affects other costs, for example energy consumption[46]. It is described by a percentual cost reduction by doubling the annual production output[43]. Here a reduction of energy between 3% and 5% was assumed when doubling the annual production output[35,48].

**Energy consumption for future's production on cell level**
For each year $y$, between 2021 until 2040, a reduction factor $f$ is calculated for percentual savings per year due to new technologies ($f_{\text{technology}}$), for percentual savings per year due to higher market share of heat pump use ($f_{\text{heatpump}}$), for percentual savings per year due to increase of cumulative production ($f_{\text{learning}}$) and for percentual savings per year due to increase of annual production ($f_{\text{scale}}$). By this for each year $y$, a percentual saving $f_{\text{sum}}$ can be calculated as

$$\begin{aligned} f_{\text{sum},y} \\ = 1 - (1 - f_{\text{technology},y}) \times (1 - f_{\text{heatpump},y}) \times (1 - f_{\text{learning},y}) \times (1 - f_{\text{scale},y}). \end{aligned} \tag{13}$$

Then $i_{\text{energy}}$ can be calculated for each future year, $y$ (here for 2040) as

$$i_{\text{energy},2040} = i_{\text{energy}} \times (1 - f_{\text{sum},2021}) \times (1 - f_{\text{sum},2022}) \ldots (1 - f_{\text{sum},2040}). \tag{14}$$

**Energy consumption on macro-economic level**
For the calculation, the following parameters are defined: the total market demand ($D$, in GWh$_{\text{cell}}$), the cell-specific market demand ($D_k$, in GWh$_{\text{cell}}$), the cell-specific market share ($S_k$, in %), the total energy demand of production to meet the market demand (ED, in GWh$_{\text{prod}}$) and the cell-specific energy demand of production to meet the market demand (ED$_k$, in GWh$_{\text{prod}}$).

The cell-specific market demand is calculated as follows:

$$D_k = D \times S_k. \tag{15}$$

The energy demand of production to meet the cell-specific market demand is calculated as followed (for electricity, natural gas and both):

$$\text{ED}_k = D_k \times i_{k,\text{energy}}. \tag{16}$$

The energy demand of production to meet the total market demand is calculated as follows:

$$\text{ED} = \sum_{k=\text{NCA}}^{\text{LAB}} \text{ED}_k. \tag{17}$$

This was calculated for all years from 2021 to 2040 (note that $D$, $S_k$ and $i_{k,\text{energy}}$ are different for each year).

We also calculated the GHG emissions resulting from global LIB and PLIB cell production, from 2021 until 2040. The results are shown in Supplementary Figs. 4 and 5. For the calculation, the following parameters are defined: the GHG emissions caused by ED (GD, in ktCO$_2$eq), the GHG emissions caused by ED$_k$ (GD$_k$, in ktCO$_2$eq), the GHG emissions per electric energy ($m_{\text{electricity}}$, in kgCO$_2$eq per kWh$_{\text{prod}}$) and the GHG emissions per natural gas energy ($m_{\text{gas}}$, in kgCO$_2$eq per kWh$_{\text{prod}}$). The calculation of ED$_k$ is as follows:

$$\text{GD}_k = m_{\text{electricity}} \times \text{ED}_k^{\text{electricity}} + m_{\text{gas}} \times \text{ED}_k^{\text{gas}}. \tag{18}$$

The calculation of ED is as follows:

$$ED = \sum_{k=NCA}^{LAB} ED_k. \qquad (19)$$

This was calculated for all years from 2021 to 2040. We used $m_{electricity}$ (2021) = 0.459 kgCO$_2$eq per kWh$_{prod}$ (ref. 49), $m_{electricity}$ (2050) = 0.160 kgCO$_2$eq per kWh$_{prod}$ (ref. 49) and $m_{gas}$ = 0.2 kgCO$_2$eq per kWh$_{prod}$. $m_{electricity}$ is linearly interpolated between 2021 and 2050.

### System boundaries and further made assumptions

This analysis was a gate-to-gate analysis. The material was excluded, and only the energy consumption of a battery cell factory was considered. It is assumed for PLIB and new LIB cells that the technical challenges in cell chemistry, cell design and production technology will be overcome and that production will take place on an industrial scale without scrap rates. Economical costs were not considered in this study.

### Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

## Data availability

The dataset generated during the current study is available within the article, its supplementary information and source data files. Source data are provided with this paper.

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## Author contributions

F.D. conceived the idea for the manuscript and designed the study. F.D. and D.B. have designed the methodical procedure together. F.D., J.T. and M.W. collected and reviewed the data. F.D. analysed the quantitative and qualitative data. F.D. wrote and revised the article. M.W., D.B. and J.T. edited the manuscript and provided comments on the manuscript.

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## Competing interests

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