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Feasibility of meeting future battery demand via domestic cell production in Europe

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Batteries are critical to mitigate global warming, with battery electric vehicles as the backbone of low-carbon transport and the main driver of advances and demand for battery technology. However, the future demand and production of batteries remain uncertain, while the ambition to strengthen national capabilities and self-sufficiency is gaining momentum. In this study, leveraging probabilistic modelling, we assessed Europe's capability to meet its future demand for high-energy batteries via domestic cell production. We found that demand in Europe is likely to exceed 1.0 TWh yr^{-1} by 2030 and thereby outpace domestic production, with production required to grow at highly ambitious growth rates of 31–68% yr^{-1}. European production is very likely to cover at least 50–60% of the domestic demand by 2030, while 90% self-sufficiency seems feasible but far from certain. Thus, domestic production shortfalls are more likely than not. To support Europe's battery prospects, stakeholders must accelerate the materialization of production capacities and reckon with demand growth post-2030, with reliable industrial policies supporting Europe's competitiveness.

Batteries are of critical importance for the rapid reduction of greenhouse gas (GHG) emissions to mitigate global warming and meet the 1.5 °C target of the Paris Agreement by enabling the widespread use of renewable electricity[1,2]. This requires transformative changes in the transportation sector[2–5] as transport accounts for approximately 20% or 7 $GtCO_2$-equivalent (7 $GtCO_2e$) of global annual GHG emissions[6], with European transport emitting ~800 $MtCO_2e$ (ref. 7).

While some studies have emphasized the difficulties involved in decarbonizing transport[4,8], there is robust evidence that battery electric vehicles (BEVs) will form the backbone of future low-carbon road transport[2,5]. Accordingly, BEVs prevail in the future portfolios of car manufacturers[9,10] and several European countries will enforce 100% zero-emission vehicle (ZEV) sales for cars by at least 2035[9–11], banning large-scale sales of conventional vehicles as sufficient quantities of sustainable fuels are unlikely[11]. Other key markets, such as the United States and China, have also set ambitious ZEV targets from the 2030s[9,11].

Regarding battery demand, electrified transport is widely recognized as the key driver[12] and catalyst for battery advances[13]. However, any projection of battery demand is highly uncertain and scenario-dependent, generally based on concealed models and subject to unclear assumptions. Hence, global demand projections for 2030 cover a wide spectrum, typically 3–6 TWh yr^{-1} and up to almost 9 TWh yr^{-1}, with European projections at around 0.7–1.4 TWh yr^{-1} (for an overview, see Supplementary Table 2).

Regarding battery production, electrification requires industrial transformation and the establishment of new battery ecosystems alongside the entire value chain from raw material extraction to end-of-life, and including concepts of circularity, such as second use or recycling[14,15]. In addition, the COVID-19 pandemic and other geopolitical tensions have created awareness of vulnerable economic dependencies and spurred the development of modern concepts such as technological sovereignty[16,17] and resilience[14,15]. In response, the European Union (EU) recently finalized the Net-Zero Industry Act[18], intending to ensure ample capacity for strategic net-zero technologies by 2030, including a target to satisfy at least 90% of its battery demand from domestic cell production[18]. Global battery production capacity is

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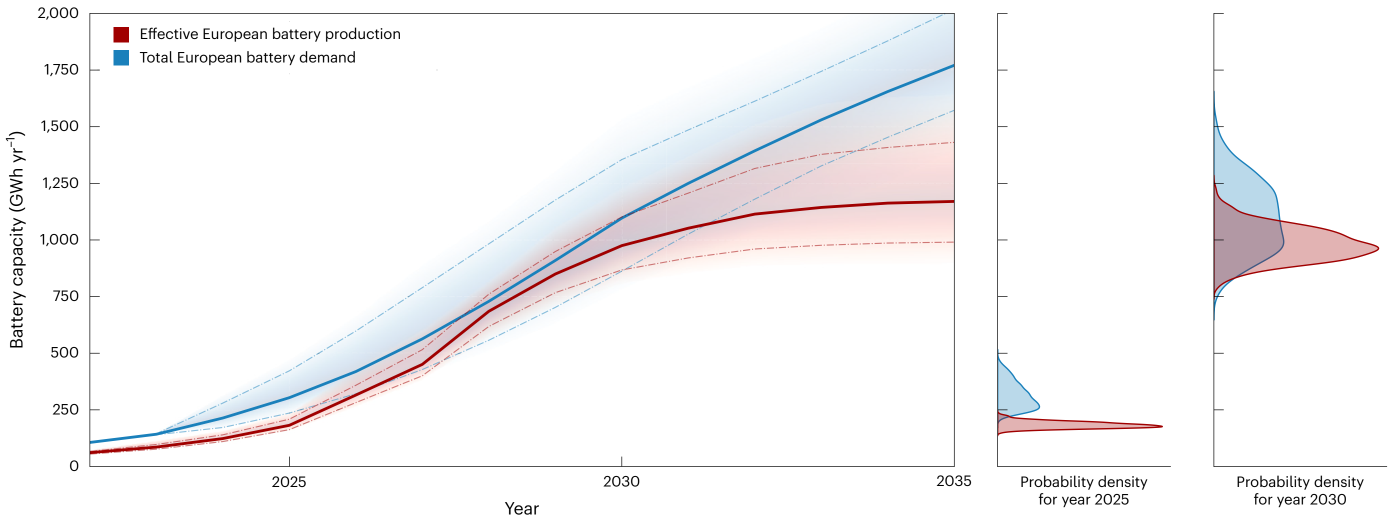

Fig. 1 | European battery demand and its domestic production capacity up to 2035. Probabilistic feasibility space for different scenarios ($N = 1{,}000$) of total battery demand and battery production capacity up to 2035 for Europe. The shaded areas show all potential model results, the dashed lines indicate the 5th and 95th percentiles, and the solid line indicates the median. Probability density plots for 2025 and 2030 are shown on the right. Reference values for production: Around 150 GWh yr^{-1} of stated capacity was available at the beginning of 2024.

expected to approach 7.0 TWh yr^{-1} by 2030, with European capacity at around 0.8–1.6 TWh yr^{-1} (for an overview, see Supplementary Table 1). However, it is unclear what proportion of the announced capacities will materialize or whether production facilities can expand fast enough to meet growing demand.

Hence, in this study, we addressed the following research question: how likely is it that Europe can cover its future battery demand via domestic production? Leveraging probabilistic modelling, we found that European demand is likely to exceed 1.0 TWh yr^{-1} by 2030 and thereby outpace domestic production, with production capacity required to grow at almost exceptionally high growth rates (31–68% yr^{-1}) over the long term with the latter's momentum increasing after 2025. However, it is very likely that Europe can cover at least 50–60% of its demand via domestic production by 2030. Even 90% self-sufficiency seems within reach, yet far from certain, so there is an increased risk of domestic production shortfalls. In contrast, if lower production capacity materializes and domestic production remains limited, this will likely pose high economic risks for Europe and imply less European battery sovereignty and setbacks for rapid climate change mitigation.

Modelling future battery demand and production

Probabilistic modelling is developing as an accurate and flexible tool to assess the feasibility of future climate change mitigation pathways[19] and modelling technology diffusion[20]. We adopted this approach to independently project future battery demand and domestic production in Europe and to evaluate Europe's pathway towards battery self-sufficiency via feasibility spaces and probabilistic statements. Accordingly, we extended the recent advances by Odenweller et al.[21], which were based on Roger's concept of technology adoption[22] and typical S-shaped diffusion curves[23].

First, we estimated domestic production using existing and announced cell production facilities and their stated capacities. There are different motivations for publicly announced production facilities and taking them at face value can easily lead to the overestimation of actual capacity and high ad hoc availability. However, uncertainties in multiyear projects are inevitable as they invariably involve delays related to construction, permits or equipment readiness, cancellations or postponements, step-by-step expansion plans, evolutionary advances in production technologies or quality issues[15,24–29]. Therefore, announced capacities usually decrease to an effective, materialized output. In our model we used $N = 144$ facilities between 2020 and 2030 in Europe, which theoretically add up to 2.55 TWh yr^{-1} by 2030. We imputed an S-shaped production ramp-up for each announcement to derive its effective, materialized annual capacity using a logistic growth model (LGM) and probabilistic parameterization of influencing factors (that is, utilization, scrap, delays and materialization probabilities). These characteristics result from two typical ramp-up phases following an earlier planning period: time-to-market and time-to-volume[30,31,27]. The time-to-market stage typically comprises pre-series and pilot production and ends with the start of production and is characterized by low utilization yet high scrap[30]. The time-to-volume stage represents the progression towards established processes with lower scrap, higher utilization and high output[30,27]. Finally, we determined the effective European production capacity per year by accumulating the individual announcements (Methods).

Second, we considered high-energy batteries for BEVs to be the main demand driver with lithium-ion batteries as the prevalent current technology. We collected historical automotive data, such as total sales and segment splits, as well as historical BEV-specific data, such as model-specific sales, installed battery capacities, segment splits and energy consumption. We combined these data with projections of future European battery demand based on probabilistic parameterization of future BEV shares, segment-specific battery capacities, segment splits, total sales and additional demand from other mobile or stationary applications. To project BEV shares, we fitted an LGM to historical BEV shares and potential future shares. Here, we assumed the potential BEV share by 2035 to follow the announced ZEV targets, and further varied the inflection point to refine the S-curve and capture an extended feasibility space for battery demand (Methods).

European demand and production approach 1 TWh by 2030

Figure 1 shows European battery demand and its domestic production capacity up to 2035. Fuelled by substantial BEV diffusion up to 2035, European battery demand is likely to surpass 1.0 TWh yr^{-1} by 2030 (in 69% of all scenarios). The interquartile range (IQR) in 2030 is 0.97–1.2 TWh yr^{-1}. Some high-demand scenarios may exceed the 1 TWh threshold as early as 2026 and even approach 1.6 TWh yr^{-1} by 2030, with the top 10% exceeding 1.30 TWh yr^{-1}. High demand may emerge from the superposition of high total sales, high BEV shares, higher segment shares for larger vehicles, larger battery capacities per segment

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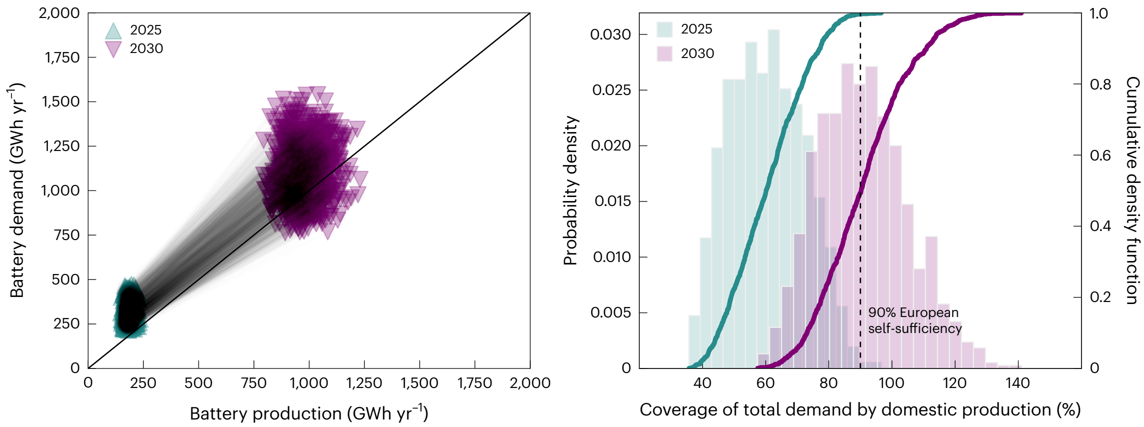

Fig. 2 | Comparison of anticipated European battery demand and supply in 2025 and 2030. Left: comparison of results of different scenarios ($N = 1{,}000$) for domestic production capacity versus demand in Europe. The trajectories for 2025–2030 are included as grey lines. The black line corresponds to supply matching demand (100%). Right: feasibility space ($N = 1{,}000$) for the relative coverage of total European demand. Probability density (histograms, left *y* axis) and cumulative density (right *y* axis) are shown for 2025 and 2030. The black dashed line marks the 90% self-sufficiency level.

and increased demand by other applications, and vice versa for low demand. Low-demand scenarios barely fall below 0.85 TWh yr^{-1} by 2030 (5th percentile). Concerning achievable BEV sales shares (Extended Data Fig. 1), the feasibility space is deemed to narrow towards 2035 due to the European ZEV regulations. Accordingly, we will most likely observe around 30% BEV sales by 2025 (median, IQR = 25–34%) and 70% by 2030 (median, IQR = 65–80%).

In contrast to the demand scenarios, the feasibility spaces for domestic production have more distinct peaks (Fig. 1). Domestic production is unlikely to surpass 1.0 TWh yr^{-1} by 2030 (39%) and the IQR is 0.93–1.04 TWh yr^{-1}. A few high-production scenarios reach 1.2 TWh yr^{-1}, with the top 5% exceeding 1.10 TWh yr^{-1}. Low-production scenarios barely fall below 0.86 TWh yr^{-1} (5th percentile). Low production capacity may emerge from the superposition of a low materialization rate, low utilization, extended delays and high scrap, and vice versa for high production.

The resulting average growth rates for demand (Extended Data Table 1) are ambitious at 31–43% yr^{-1}, but they have been witnessed for other technologies. Historically, wind and solar capacity growth rates have been at least 15% yr^{-1} and often between 39 and 50% yr^{-1} (ref. 21). General technology adoption growth rates have typically been below 13–14% yr^{-1}, but occasionally have exceeded 30–40% yr^{-1} (ref. 32). In contrast, the calculated growth rates for production are more ambitious, ranging from 55 to 68% yr^{-1}, and close to the levels witnessed historically in times of emergency when unconventional rates of growth were observed, as indicated by Odenweller et al.[21]. Accordingly, if such exceptional growth rates were not realized, we would observe substantially lower European production capacity by 2030, affirming that materialized capacity expands more slowly than announcements might suggest.

Self-sufficiency of 90% in 2030 is feasible but far from certain

Figure 2 shows the individual scenarios as trajectories (left) and density plots with cumulative density (right) for production versus demand for 2025 and 2030. It is very likely that domestic production can meet at least 60% of demand in 2025 (90.1%) and 2030 (99.5%), although the results for 2025 reveal a slightly elevated risk of short-term domestic production shortfalls. For 2030, the 90% self-sufficiency target seems feasible as this corresponds to the mean and median value (IQR = 80–100%), but is far from certain as nearly half of the scenarios (49%) do not reach the 90% self-sufficiency target. Production capacity exceeds domestic demand by more than 10% in a minor share of scenarios (11%).

Our results are stable, even if we replace the LGM with Gompertz or Bass diffusion models to capture asymmetric growth (Extended Data Fig. 3a,b). The results from the Gompertz model show narrower feasibility spaces at lower growth rates (20–27% yr^{-1} for demand and 31–48% yr^{-1} for production, Extended Data Table 1) and an aggravated shortfall of domestic production capacity, particularly around 2025. Moreover, if we limited the growth rates (15–39% yr^{-1}) for the total production capacity using the Gompertz model (Extended Data Fig. 3c), we would observe ~0.89 TWh yr^{-1} by 2030 (IQR = 0.84–0.96 TWh yr^{-1}) and exceeding 1 TWh would be more unlikely (15%). Accordingly, the 90% self-sufficiency target would be even more at risk (25%), while at least 50% self-sufficiency would still be very likely (98.1%, median = 83%, IQR = 75-90%).

Growing engagement of European companies

Beyond mere domestic production capacity and self-sufficiency, the company's origin is relevant in the context of accessibility and technology sovereignty. While the corporate landscape was nearly 100% Asian in the early 2020s, the share of European companies is projected to increase substantially. In 2025, around two-thirds of the materialized production capacity is likely to result from Asian-affiliated companies and more than one-third from European companies (Extended Data Fig. 2). By 2030, European companies are projected to hold the largest share (45–55%), while the share of Asian companies is expected to decline (40–50%) with US companies anticipated to capture modest shares (3–8%).

Europe's position on battery raw materials is improving

The complexity of battery value chains[13,33] implies that production capacity should be assessed alongside raw material sourcing, where domestic availability is a decisive factor for Europe and also for other countries[34,35]. Expressing the European battery demand in terms of required raw material quantities reveals that the cumulative demand for key materials, namely, nickel, cobalt, graphite, lithium and manganese, is projected to increase substantially by 2035, with expected 9-fold (cobalt) and 12–15-fold (nickel, manganese, graphite and lithium) increases relative to the quantities required in 2025 (Table 1). While Europe will rely on raw material imports until 2030–2035, three factors indicate a strengthening position. First, and in relation to expected demand, substantial domestic reserves of manganese and natural graphite are available, with possibly lower prospects for lithium and nickel, but primary cobalt is scarce. Second, existing self-sufficiency assessments (Table 1, rightmost column) indicate progress in building

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Table 1 | Overview of European demand, production, reserve (primary) and resource (primary) data for five critical battery raw materials

Material (unit)	Annual values (kt yr^{-1})			Cumulative values (kt)				Potential European self-sufficiency by 2030 (%)
	Current European production	Demand by 2025	Demand by 2035	Demand by 2025	Demand by 2035	Current European reserves	European resources	
Li (kt LCE content)	P: <1 R: NA	30±6	170±10	100±10	1,230±130	60–470	6,700–7,000	P: 25–60 R: 27–85
Ni (kt Ni content)	P: ~50 R: ~70	180±30	820±90	510±50	6,170±700	~5,200	~12,300	P: 20–23 R: 20–28
Co (kt Co content)	P: ~50 R: <10	40±8	120±20	130±10	1,150±150	90–340	520	P: 1–20 R: 20–37
Mn (kt Mn content)	P: <7 R: NA	50±10	320±40	150±10	2,140±260	~2,000	~2,000	P: 45–100 R: 28–100
Gr (kt refined graphite)	P: <15 R: NA	260±50	1,520±120	730±80	10,360±1,070	2,000–7,500	~30,900	P: <5 R: 21–26

All values are rounded and specified in kilotonnes. Demand values (refined and battery-grade quality) are specified as mean ± standard deviation. The ranges for potential European self-sufficiency for each material by 2030 (without recycling) are based on literature data; reference details and original values are provided in Supplementary Tables 22 and 23. Calculated demand values and data for 2030 are provided in Supplementary Tables 25 and 26 and visualized in Supplementary Figs. 2 and 3. P, primary; R, refined, battery quality; Li, lithium; LCE, lithium carbonate equivalent; Ni, nickel; Co, cobalt; Mn, manganese; Gr, natural graphite; NA, not available.

European value chains, however, ramp-ups must be extremely quick. While cobalt and nickel imports (all grades) are likely to remain necessary for domestic processing, it is likely that major shares of lithium and most of the manganese can be sourced and refined domestically. Natural graphite (all grades) is likely to require both local sourcing and refining as well as imports. However, global supply diversification is anticipated to also lower general dependency risks[36,37]. Third, emphasizing the circular economy and recycling, as proposed in the EU's Critical Raw Materials Act[38] or incentivized by the US Inflation Reduction Act[35], is likely to reduce dependency and further improve sustainability within a comprehensive battery ecosystem[13,39–41], also securing material availability even beyond 2050[42]. Yet, current estimates of battery returns[36,43,44] strongly indicate that recycling or second use/repurposing of batteries will be less relevant in the early 2030s, but will sharply grow in importance thereafter, in particular, unlocking potential for nickel[37,43] and cobalt[41]. In addition, battery technologies such as sodium-ion batteries are an intended alternative to lithium-ion batteries; these are currently at the beginning of large-scale commercialization[24,45].

Uncertainties and policy implications

Our results indicate that the course has been set for transitioning from battery research and development (R&D) to production and establishing value chains in Europe. While substantial capacity additions can be expected until 2030, reaching the adopted EU 90% self-sufficiency target by 2030 is highly challenging as production capacity would require a highly ambitious growth rate. Nonetheless, our results imply that the domestic production of batteries is unlikely to be a bottleneck for BEV market diffusion in Europe and will conform to the transport-specific emission budgets required to comply with the 1.5 °C global warming target (that is, ~70% ZEV sales by 2030 and 100% by no later than 2033[5]).

However, our analysis has limitations related to probabilistic parameter choice and parameter assumptions, independent modelling with missing feedback mechanisms, data availability or neglected vehicle trading. Nevertheless, our individual projections align with other studies (Supplementary Tables 1 and 2), and furthermore, we have demonstrated robustness by varying the diffusion models and certain parameters.

First, parameters were sampled from independent programme evaluation review technique (PERT) distributions (Methods). Specific minimum, most likely and maximum values were primarily based on literature values, but some were in-house assumptions and projections based on recent developments. While this implies representative feasibility spaces per parameter, real-world distributions are unknown, parameter dependencies were disregarded and potential trend breaks may have been missed, such as declining popularity in sport utility vehicles (SUVs) or shrinking battery sizes. Future studies could further decompose parameters such as demand from other applications.

Second, capturing dependencies and feedback mechanisms between supply and demand might constrain the joint feasibility space as substantially decoupled scenarios, such as high production with low demand or vice versa, may be deemed improbable. Similarly, demand scenarios where BEV ranges remain low but their sales shares rise high may be considered improbable, given that perceived range anxiety remains a significant barrier for many potential buyers[46,47]. Future studies could use other approaches, such as system dynamics.

Third, production capacities were derived from individual announcements (bottom-up, cut-off January 2024) rather than model-based or demand-driven outlooks (top-down), confining our dataset and results. On the one hand, we emphasize that the lack of standardization makes it difficult to distinguish what is or is not accounted for in the announced capacity. If capacity utilization were included, we would obtain higher production capacities by 2030 (IQR = 1.15–1.30 TWh yr^{-1}) with unrestricted growth rates and an almost parallel trend slightly below demand with limited growth rates (Extended Data Fig. 4a–c). On the other hand, as there are no explicit announcements beyond 2030, supply curves flatten towards 2030 even though our model accounts for delayed realization, potentially leading to underestimated production capacities between 2030 and 2035. Of course, additional capacities may emerge after 2030. However, no announcements have been made so far, even though there are only 5 years left before this date and not every factory is likely to expand at short notice.

Fourth, we linked domestic battery demand to domestic sales, assuming that European sales equal production figures and neglecting any foreign trade, as with the batteries themselves. While total European vehicle sales and production figures are a good match (±10%), exports dominated imports in the trade balances from 2015 to 2022, with clear distinctions between imported (smaller and volume-type) and exported (larger and more premium-type) vehicle segments.

In our analysis, we disregarded upstream and downstream parts of the value chain that might constrain Europe's prospects too. Most notably, capacity for the refinement of raw materials as well as producers of further processed cathode and anode active materials (CAMs and AAMs) and cell components will be required to supply factories domestically. In this respect, there have been several announcements in Europe, with more progress for CAM processing[27] than for AAMs[48]. Nevertheless, most of the announced battery cell plants are likely to have secured long-term supply contracts, mitigating the risk of material shortages. Finally, the current shortage of skilled workers may continue to outpace the build-up in Europe[15,24,25]. This shortage affects scientific and industrial R&D at all technology readiness levels, as well as direct and indirect jobs in the sector, from factory build-up to cell manufacturing and system-level integration. Future studies could adapt our probabilistic modelling to integrate these aspects.

Focusing on the implications for decision-makers in policy and industry, Europe is striving for a competitive and sustainable battery ecosystem with concrete agendas and roadmaps[49], including the Net-Zero Industry Act[18]. This includes launching several initiatives and public–private partnerships, such as Batteries Europe and the Batteries Europe Partnership Association, or funding under the framework of the Important Projects of Common European Interest to align industry and policy perspectives on cross-cutting issues such as scale-up, sustainability, recycling and digitalization[50]. In addition, there are special trade and cooperation agreements, such as the EU–UK Battery Rules of Origin.

Although there is likely no single policy strategy to boost battery ecosystems, we highlight the role of industrial policies in balancing trade protectionism and global competitiveness. While the current EU battery policy has a supply-side emphasis with many initiatives focusing on R&D[50], recent initiatives such as the Strategic Technologies for Europe platform[51] or the Temporary Crisis and Transition Framework[52] have an explicit focus on industrial development, competitiveness and sovereignty. Recent examples, such as the Northvolt battery factory in Germany[53], indicate that such industrial policies might be effective in spurring domestic projects (irrespective of an individual company's future development). The global race might call for policies that create attractive, predictable home markets[33] and reduce the risks for industry players, such as public–private risk–reward–sharing instruments, while purely inward-looking policies might be rather detrimental[17,54]. Regarding prioritization, we emphasize that establishing fully scaled and sustainable value chains simultaneously presents enormous challenges and the inherent risk of impeding fast competitiveness. China, for instance, started building internationally competitive battery value chains years ago, leads current battery R&D, employs an extensive specialized workforce, and is now progressing towards more circular, safer and more sustainable batteries[50]. Finally, we highlight the importance of using net materialized production capacities as a basis for projections rather than announced capacities, which fail to consider scrap rates, new technology developments, non-optimal capacity utilization or delays related to construction and permits.

For industry players, our results indicate substantial potential for domestic added value, tailoring batteries to Europe's needs, as well as localizing raw material production and battery recycling. Moreover, our results call for further investments in local battery production to avoid shortages in domestic production, while keeping track of international developments.

Conclusions

In this study, we used probabilistic modelling of S-shaped production ramp-up and technology diffusion based on the latest empirical data to project future battery demand and domestic production in Europe. This allowed us to evaluate Europe's prospects towards battery self-sufficiency via feasibility spaces and probabilities in a consistent, transparent and thorough manner. Based on our results, we can draw four main conclusions.

First, we have shown that European demand is likely to experience ambitious growth to at least 1.0 TWh yr^{-1} by 2030. In contrast, domestic production capacities are more likely to fall behind terawatt hour scales by 2030, with momentum increasing after 2025 and production capacities required to grow at unconventional growth rates.

Second, the prospects for a European footprint along the battery value chain are remarkable. On the one hand, covering at least 50–60% of its demand via domestic production by 2030 is very likely and the contribution from European-affiliated companies is projected to grow substantially, while potential to improve the raw material situation in Europe also exists. On the other hand, 90% self-sufficiency by 2030 seems feasible but far from certain. We thus emphasize an increased likelihood of limited European competitiveness and domestic production shortfalls, particularly before 2030.

Third, the short-term volatility of battery demand, mainly caused by uncertain BEV popularity and availability, should not unsettle investment decisions and detract from long-cycle commitments based on GHG mitigation, manufacturer announcements, and ZEV targets in Europe and automotive core markets worldwide. Note that international ZEV targets will also restrict European export capacity for non-BEVs in the future.

Fourth, the global battery manufacturing race, complex value chains, raw material dependencies and time-consuming ramp-ups stress the urgency of immediate action and reliable policies to lower risks and ensure certain predictability. Without these, Europe's need to import batteries is likely to persist, or even increase, thus keeping Europe dependent on imports in a key technology for current and future sustainable transport and energy.

Methods

General approach

We used probabilistic modelling of S-shaped production ramp-up and technology diffusion based on the latest empirical data to project future battery demand and domestic production in Europe, covering the EU, the European Free Trade Association (EFTA) and the United Kingdom. We also translated this battery demand into the corresponding amounts of required critical raw materials. This probabilistic approach captures the nonlinear propagation and simultaneous interaction of major parameters with inevitable uncertainties, in contrast to deterministic models that rely on single estimate inputs. However, the goodness of the projections still depends on the quality of the input data and chosen model parameterization. A Monte Carlo simulation ($N = 1,000$) then allows the construction of feasibility spaces and the classification of findings by probability. The model was implemented in Python. Model components and procedures are illustrated in Supplementary Fig. 1. We performed all calculations on a standard Lenovo notebook with an i7-8565U @1.8 GHz processor and 16 GB RAM (random access memory).

Parameter documentation

We provide comprehensive data tables for each modelling parameter, including further information and data sources, in the Supplementary Information (production parameters in Supplementary Tables 3–7, demand parameters in Supplementary Tables 8–18 and raw material parameters in Supplementary Tables 19–23).

Data on announced battery production capacities

We collected data on existing and announced battery production facilities from the Fraunhofer Institute for Systems and Innovation (ISI) database, which lists 144 European projects for the period 2020–2030. The database includes details of development status/risk level (secure, likely or insecure), technology characteristics, company information and, most importantly, annual production capacities for the announced projects, totalling 2.55 TWh yr^{-1} by 2030. The dataset for this study, as of January 2024, is available at Zenodo via https://doi.org/10.5281/zenodo.14505410 (ref. 55), while the latest aggregated version can be accessed at https://metamarketmonitoring.de/en/.

Historical automotive data

We used data published by the European Automobile Manufacturers' Association[56] and JATO Dynamics[57] for general automotive market data. These data comprise European sales until 2023 and segment-specific shares (first half of 2022) covering the EU, EFTA and the United Kingdom. We differentiated between the AB segment (mini and small vehicles), the CM segment (compact cars and multipurpose

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vehicles), the DEF segment (large and premium-type vehicles) and the SUV segment. The SUV system is split into small and medium (SM) and large (L) vehicles.

Historical BEV-specific data

We obtained BEV-specific data (see Link et al.[58]), comprising sales data and comprehensive information on installed batteries until 2022, from the Fraunhofer ISI xEV battery database. Based on these data, we calculated sales-weighted average battery capacities per segment and BEV-specific segment splits covering the EU, EFTA and the UK. The gross battery capacities were derived by assuming an average share of usable energy of 93% (ref. 59). The segment-specific BEV energy consumption was calculated on the basis of European CO_2 certification data, as prescribed under Regulation (EU) 2019/631 and provided by the European Environment Agency[60]. We evaluated all vehicles with specific CO_2 emissions of 0 $gCO_2e\ km^{-1}$ (by the World Harmonized Light Vehicles Test Procedure). These data are available up to 2022 and cover the EU, the United Kingdom (until 2019), Iceland (from 2018) and Norway (from 2019). We assumed energy consumption improvements of at least 5% until 2030–2035 due to increased energy efficiency or road load reductions. The latter mainly concern lightweight materials and decreasing battery weight[61–63] as there is increasing evidence that higher specific energy levels and enhanced system integration overcompensate increasing battery sizes.

Modelling the effective, materialized domestic production capacity

First, we used the announced annual production capacities (in GWh yr^{-1}) as the base matrix, where each project corresponds to a row and each column to a year from 2020 to 2030. We extrapolated 2030 values to 2035. The year in which the first batteries were announced marks the start-up year.

Second, we used matrix multiplication to add four influencing factors via probabilistic parameterization: (1) capacity utilization, where we used the overall equipment effectiveness as proxy, (2) scrap rates, (3) project delays or postponements and (4) materialization categories. This results in the probable production capacity. Specifically, modelling the evolution of overall equipment effectiveness (OEE) is announcement-specific, starting with an initial OEE (oee_0) in the first year. We then assumed a gradual increase to the target OEE (oee_T) over several years (T_{OEE}) using linear interpolation. All three values were drawn from PERT distributions (Supplementary Table 4). Accordingly, the OEE matrix contains the evolution of OEE for each project from its start-up year until 2035. Similarly, modelling the evolution of the scrap rate is announcement-specific, starting with high initial scrap rates (sr_0) in the first year. We then assumed a gradual decrease to the target scrap rate (sr_T) over several years (T_{SR}) using linear interpolation. Again, all three values were drawn from PERT distributions (Supplementary Table 5). Accordingly, the scrap matrix contains the evolution of scrap rate for each project from its start-up year until 2035. Modelling potential delays or postponements (t_{Delay}) is announcement-specific, whereas values depend on the risk level (secure, likely or insecure) and were drawn from PERT distributions (Supplementary Table 7). Finally, modelling the probability of materialization (p_{Mat}) is announcement-specific, whereas values depend on the risk level (secure, likely or insecure) and were drawn from PERT distributions (Supplementary Table 6).

Third, we fitted each announcement and its probable production capacity using an LGM. This smooths the data and captures the S-curve-shaped production ramp-up. Curve fitting was conducted using the Python SciPy software package[64]. We determined the materialized European production capacity per year by accumulating the individual fitted announcements, where we again used curve fitting to determine certain indicators, such as total growth rate and inflection point.

Logistic growth model

The empirically observed S-shape over time emerges because of exponential growth/progress in the initial phase, which slows over time and gradually approaches an asymptotic maximum. The accompanying standard logistic growth model is defined as follows:

$$C(t) = \frac{C_{\mathrm{Max}}}{1 + \mathrm{e}^{-k(t-t_{\mathrm{infl}})}} \quad (1)$$

where $C(t)$ is the output over time t, C_{Max} is the asymptote, k is the growth constant, t_{infl} is the inflection point and e is Euler's number.

Other diffusion models

Other common diffusion models, such as the Gompertz (equation (2)) or Bass diffusion (equation (3)) models, allowed us to capture asymmetric growth and compare the results with those of the symmetric LGM model. Both models are defined as follows:

$$C(t) = C_{\mathrm{Max}} \times \mathrm{e}^{-\mathrm{e}^{-k(t-t_{\mathrm{infl}})}} \quad (2)$$

$$C(t) = C_{\mathrm{Max}} \times \frac{1 - \mathrm{e}^{-(p+q)t}}{1 + \frac{q}{p} \times \mathrm{e}^{-(p+q)t}} \quad (3)$$

where q is the coefficient of imitation and p is the the coefficient of innovation.

Battery demand from BEVs

The European battery demand from BEVs results from the probabilistic parameterization of future BEV sales shares, battery capacities per segment, BEV-specific segment shares and total vehicle sales. Future parameters were calculated until 2035. The interim values were calculated via linear interpolation using the future target and historical values as references.

Future battery capacities result from segment-specific target ranges for 2030–2035. Targets were inspired by the European Council for Automotive R&D (EUCAR)[65], which specifies 400 km for average short-range vehicles and 600 km for long-range vehicles. Concrete range values were drawn from segment-specific PERT distributions. We then calculated the gross battery capacity by using segment-specific energy consumption and accounting for the average share of usable energy. The segment-specific BEV energy consumption was drawn from PERT distributions based on historical values[60] and potential efficiency improvements.

Total vehicle sales were projected on the basis of the correlation of gross domestic product (GDP) and automotive sales, with sales historically anticipating GDP growth. Specifically, we followed GDP expectations from the International Monetary Fund (IMF) and Organisation for Economic Co-operation and Development (OECD) for the rest of the 2020s, and matched historical year-on-year sales growth rates with historical GDP growths to determine their relation. Concrete sales growth values were then drawn from PERT distributions using this relation.

For segment-specific BEV sales shares, we assumed a uniform diffusion of BEVs across all segments until 2035, as well as the continuation of ongoing trends such as the SUV boom. More precisely, we initiated the BEV-specific split for each segment in 2022 and gradually aligned this share with the projected total market segment split until 2035. For the latter, we used the historical evolution of segment shares (compound annual growth rate for 2011–2022) and the total market segment shares by 2023 as references. Concrete growth rate values were drawn from PERT distributions. Finally, the total share of all segments was normalized to 100%.

For BEV sales shares, we fitted an LGM to historical BEV sales data (2015–2023) and potential future sales. Specifically, we added a potential inflection point and BEV sales shares by 2035 using probabilistic parameterization. This inflection point affects the shape of the

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BEV market diffusion and is intended to approximate various strategies from BEV boosts to delays. For 2035 and beyond, we followed the announced emission regulations of most European countries, meaning that (nearly) all new cars must be ZEVs (that is, locally emission-free vehicles with 0 $gCO_2e\ km^{-1}$ exhaust emissions). We defined 90% BEV share as the lower limit and 100% as the upper limit. Final curve fitting was achieved using the Python SciPy package[64], and the final asymptote (C_{Max}), growth rate (k) and actual inflection point (t_{infl}) were calculated.

The final European battery demand from BEVs was then calculated by multiplying the battery capacities per segment, segment-specific sales shares, BEV sales shares and total vehicle sales.

Total battery demand

The final European battery demand from BEVs was then scaled up by the demand from other first-life applications to derive the total battery demand. This includes other automotive applications, such as plug-in hybrids, electrified commercial vehicles (trucks and buses) and light-electric vehicles. In addition, stationary systems, from home to industrial-scale buffer storages, are likely to evolve as the second largest market if electrification and the integration of renewables are pushed globally and locally, especially in Europe. Concrete scaling values were drawn from PERT distributions.

Raw materials

The quantities of required raw materials were calculated using three average cathode stoichiometries (that is, medium-nickel, high-nickel and iron- or manganese-based materials according to Maisel et al.[66]) and the accompanying specific material demand (in $g\ Wh^{-1}$). Potential cathode chemistry market shares for 2035 were drawn from PERT distributions and normalized, with values between 2024 and 2034 being derived via linear interpolation. All modelling parameters and detailed references are provided in Supplementary Figs. 2 and 3 and Supplementary Tables 19–26. Please note that the model therefore estimates the amount of raw material input required to produce the battery cells. The model does not, however, take into the consideration the fact that the actual ramp-up and construction of European mining capacity will require additional time.

PERT distribution

The PERT distribution is frequently used in risk analysis and corresponds to a re-parameterized/transformed beta distribution. The PERT probability distribution function is defined as:

$$f(x, x_{\min}, x_{\mathrm{ml}}, x_{\max}) = (x_{\max} - x_{\min})\frac{1}{B(\alpha,\beta)}x^{\alpha-1}(1-x)^{\beta-1} + x_{\min} \quad (4)$$

where x is the realized value, $x_{\min}$ is the minimum, x_{ml} is the most likely value and $x_{\max}$ is the maximum. The beta function B and shape parameters α and β are defined as:

$$B(\alpha,\beta) = \int_0^1 t^{\alpha-1}(1-t)^{\beta-1}\mathrm{d}t$$

$$\alpha = 1 + \lambda \times \frac{x_{\mathrm{ml}} - x_{\min}}{x_{\max} - x_{\min}},\ \lambda = 4$$

$$\beta = 1 + \lambda \times \frac{x_{\max} - x_{\mathrm{ml}}}{x_{\max} - x_{\min}},\ \lambda = 4 \quad (5)$$

Data availability

All data are available in Supplementary Tables 3–18 and within the Python model. Data can be accessed at Zenodo via https://doi.org/10.5281/zenodo.14505410 (ref. 55). Source data are provided with this paper.

Code availability

The Python model code can be accessed at Zenodo via https://doi.org/10.5281/zenodo.14505410 (ref. 55).

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Author contributions

S.L. and L.S. conceived and designed the study in consultation with P.P. S.L. and L.S. collected the data, implemented the model and created the visualizations. S.L. wrote the original paper with contributions and revisions from all authors. P.P., A.S. and L.W. contributed to the discussion, interpretation of findings, recommendations and policy implications. P.P. supervised the study.

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Competing interests

The authors declare no competing interests.

Additional information

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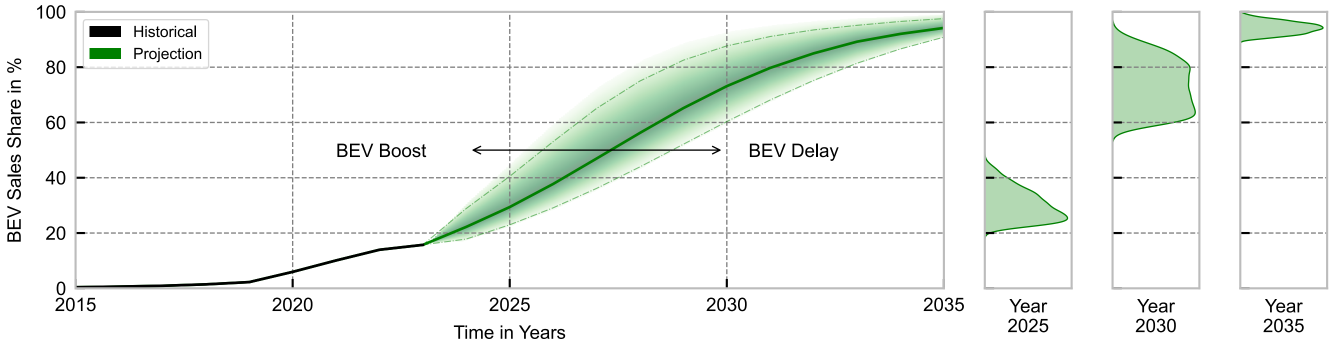

Extended Data Fig. 1 | Probabilistic feasibility space (N = 1,000) for BEV sales shares until 2035. Logistic growth model (LGM). Historical values are in black (until 2023) and projections are in green. Shaded areas mark all model results, while the dashed lines indicate the 5% and 95% percentiles, and the solid line indicates the median. Probability density (PD) plots for 2025, 2030, and 2035.

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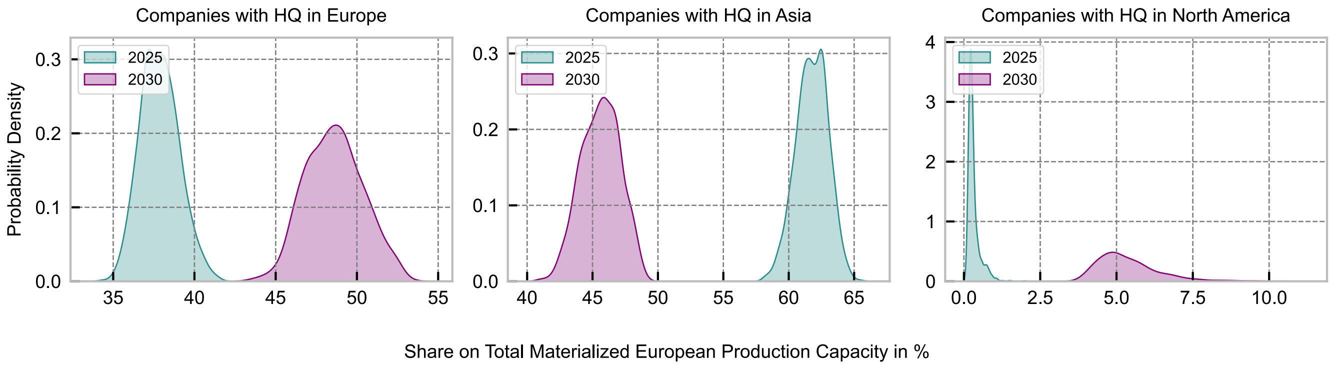

Extended Data Fig. 2 | Probabilistic feasibility space (N = 1,000) for production capacities differentiated by the company's country affiliation (location of headquarter (HQ)). Covering Europe (left), Asia (middle), and North America (mainly the US, right), visualized as density plots. Logistic growth model (LGM). Probability densities for 2025 (teal) and 2030 (purple).

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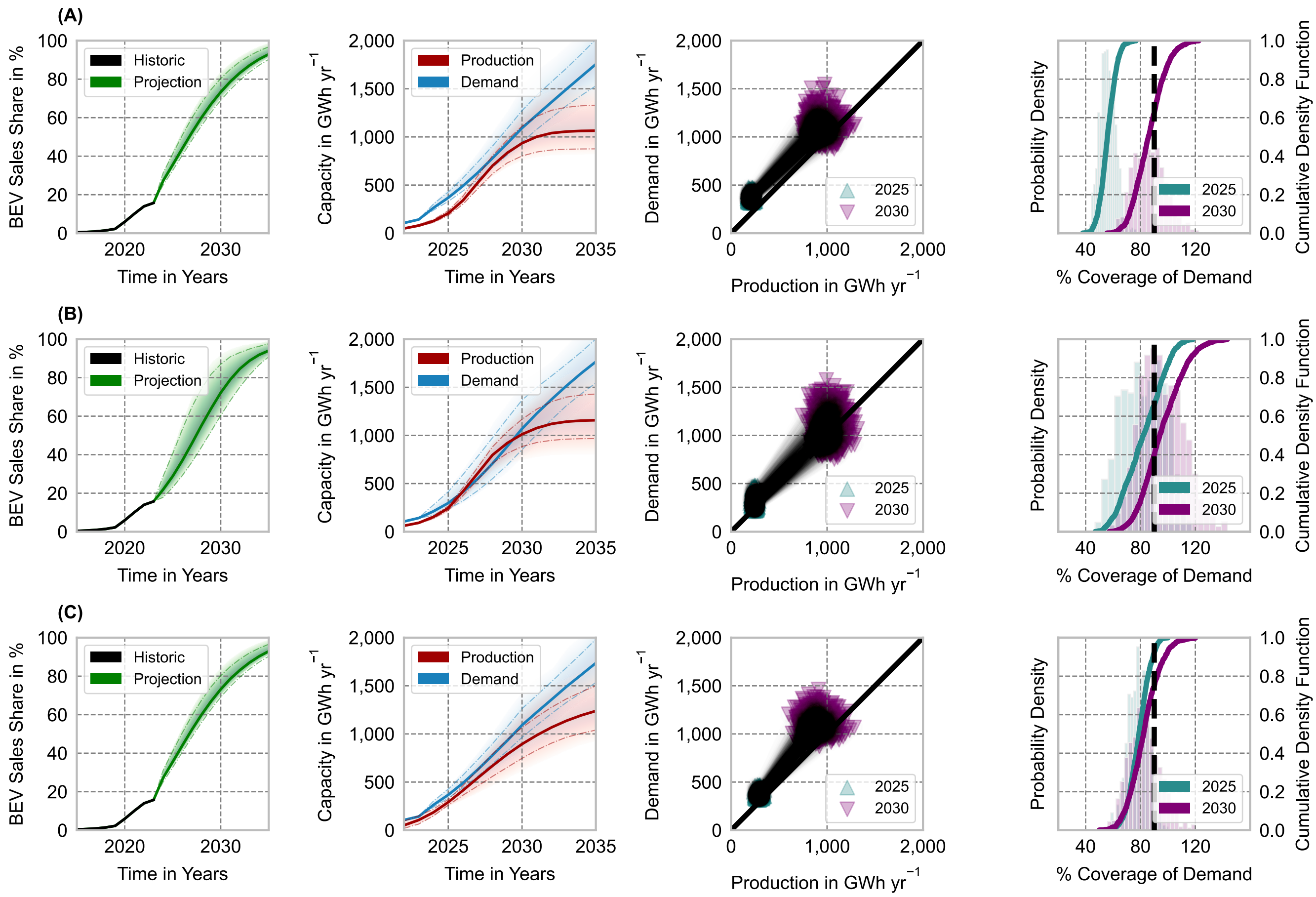

Extended Data Fig. 3 | Sensitivity with different diffusion models. Gompertz diffusion model (Upper-A), Bass diffusion model (Middle-B), and Gompertz diffusion model with limited growth rate (Lower-C) - N = 1,000. (1): BEV sales shares until 2035. Historic values are in black (until 2023) and projections are in green. Shaded areas mark all model results, while the dashed lines indicate the 5% and 95% percentiles, and the solid line indicates the median. (2): BEV battery demand (blue) versus battery production capacity (red) until 2035. Shaded areas mark all the potential model results, while the dashed lines indicate the 5% and 95% percentiles, and the solid line indicates the median. (3) Comparison for domestic production capacity (x-axis) versus demand (y-axis) in GWh yr^{-1} for 2025 (teal triangle) and 2030 (purple diamond), including trajectories. (4) Feasibility space for relative coverage of total European demand for 2025 (teal) and 2030 (purple), including the 90% self-sufficiency level (black dashed line). The results for 2025 (teal) and 2030 (purple) are shown as histograms (left y-axis, no ticks) and cumulative density (right y-axis).

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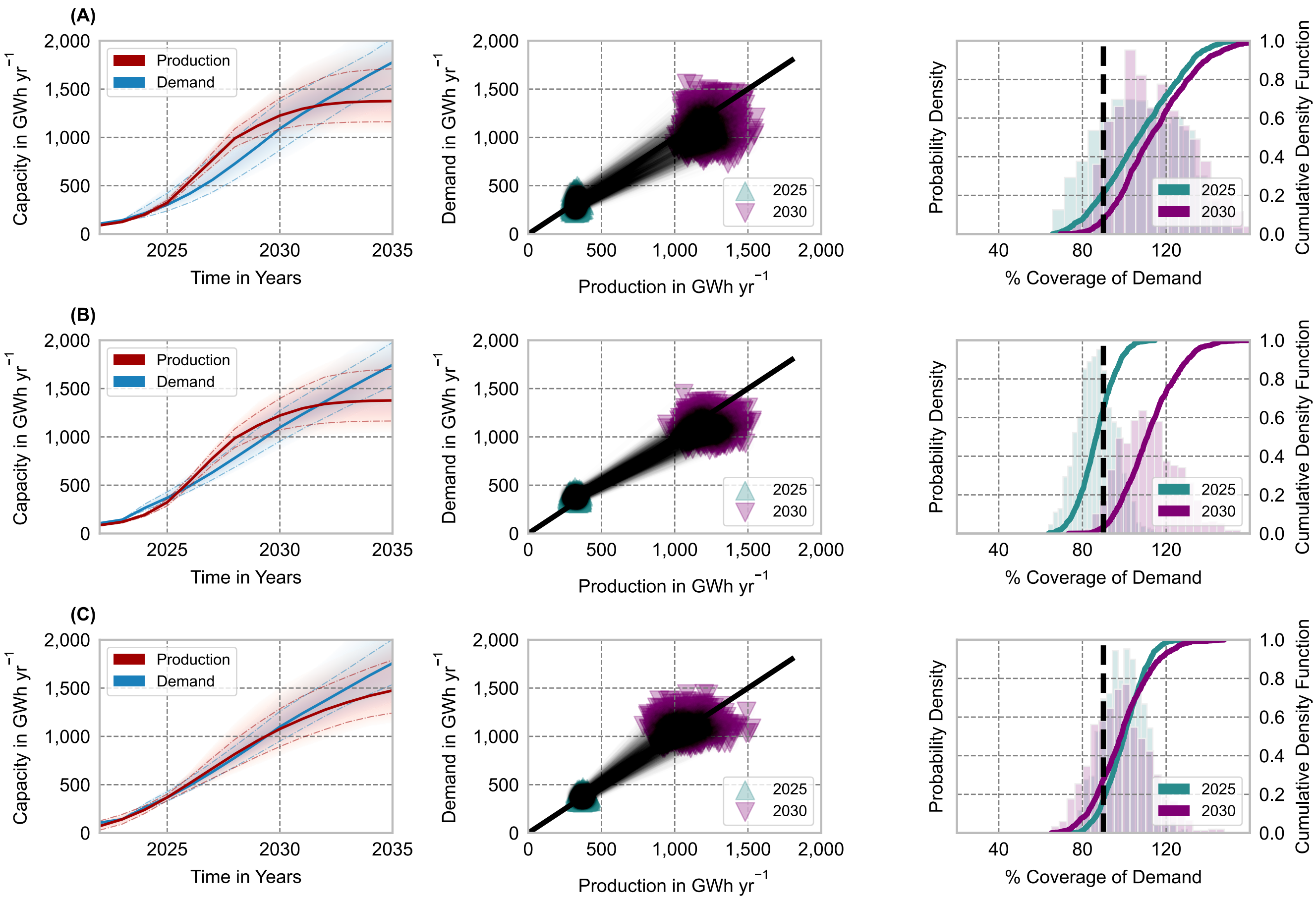

Extended Data Fig. 4 | Sensitivity without utilisation constraint. Logistic growth model (Upper-A), Gompertz diffusion model (Middle-B), and Gompertz diffusion model with limited growth rate (Lower-C) - N = 1,000. (1): BEV battery demand (blue) versus battery production capacity (red) until 2035. Shaded areas mark all the potential model results, while the dashed lines indicate the 5% and 95% percentiles, and the solid line indicates the median. (2) Comparison for domestic production capacity (x-axis) versus demand (y-axis) in GWh yr^{-1} for 2025 (teal triangle) and 2030 (purple diamond), including trajectories. (3) Feasibility space for relative coverage of total European demand for 2025 (teal) and 2030 (purple), including the 90% self-sufficiency level (black dashed line). The results for 2025 (teal) and 2030 (purple) are shown as histograms (left y-axis, no ticks) and cumulative density (right y-axis).

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Extended Data Table 1 | Statistical figures for calculated growth rates and inflection points for demand and production via the Logistic Growth Model (LGM) and Gompertz (GOM)

Parameter	Target	Model	Median	IQR	5% percentile	95% percentile
Growth Rate (% per year)	Demand	LGM	36.2%	10.3% (43.0%-32.8%)	31.3%	52.9%
		GOM	22.1%	2.6% (23.6%-21.1%)	20.5%	26.5%
	Production	LGM	61.8%	5.8% (64.7%-58.9%)	54.9%	68.0%
		GOM	37.3%	5.0% (39.8%-34.7%)	30.8%	43.0%
Inflection Point (year)	Demand	LGM	2027.3	2.0 (2028.4-2026.4)	2025.6	2029.0
		GOM	2025.4	0.5 (2025.6-2025.1)	2024.6	2025.8
	Production	LGM	2027.6	0.5 (2027.8-2027.3)	2027.1	2028.2
		GOM	2026.4	0.4 (2026.6-2026.2)	2027.1	2026.0

This involves the median (first column), the interquartile range (IQR, second columns), as well as the 5% (third column) and 95% percentiles (fourth column). Growth rates as percentage values. Inflection points in years.