Drive Down the Cost: Learning by Doing and Government Policies in the Global EV Battery Industry*

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Preliminary. October 2024

Abstract

Electric vehicle (EV) battery costs have dropped by more than 90% over the past decade. This study assesses the extent to which this sharp decline in battery costs is attributable to learning-by-doing in battery production, and quantifies the impact of two types of government policies (consumer subsidies and local content requirements) on learning and industry dynamics. Utilizing rich data on product attributes and battery suppliers for every EV model sold in 13 top EV countries, we estimate a structural model of the global EV industry to recover battery costs for each EV model by accounting for consumer choices, EV makers' pricing decisions, and bilateral bargaining between EV makers and battery suppliers over battery prices. Learning-by-doing, estimated at a rate of 8.6%, greatly magnified the impact of consumer subsidies on EV adoption and led to positive complementarity among subsidies in different countries. European subsidies and US subsidies benefited other regions more than Chinese subsidies, partly because of larger import shares and a greater extent of sourcing from foreign battery suppliers. China's whitelist policy, which required automakers to use domestically produced batteries to receive EV subsidies, generates significant business stealing while inhibiting the positive global spillovers from consumer subsidies.

Keywords: Learning-by-doing, batteries, EVs, subsidies, local content

JEL Classification: F13, L52, L62, Q48

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1 Introduction

Electrifying passenger transportation through the widespread adoption of electric vehicles (EVs) and simultaneously transitioning to a cleaner electricity grid is a crucial strategy in mitigating climate change. Many countries have set ambitious targets for transportation electrification and have implemented various policies to support the adoption of EVs. The high upfront cost of EVs, largely driven by the expensive lithium-ion batteries they use, continues to be a major barrier to broader adoption. While the cost of EV batteries has decreased by almost 90% between 2010 and 2020 (Bloomberg NEF, 2020), additional reductions are necessary if EVs were to become more widely affordable. Industry experts recognize learning-by-doing (LBD) as a key factor in the significant reduction of battery costs. As experience accumulates, unit production costs decrease, driven by reductions in scrap rates and improvements in production efficiency. Other factors, such as technological progress and changing supply conditions, might also have played a role in the historical decline in battery costs. Despite the importance of battery costs in the diffusion of EV technology, there is a lack of credible causal evidence on the size and nature of LBD, and limited understanding of how LBD interacts with various government policies in the EV industry. This paper aims to address these gaps.

The main objectives of this paper are twofold: a) to quantify LBD and its contribution to the observed reduction in EV battery costs over time; and b) to assess how LBD interacts with the two classes of government policies (consumer subsidies and local content requirements) on global and domestic EV diffusion, market shares dynamics, and social welfare.

Quantifying LBD is crucial for understanding the broad impacts of two prominent classes of policies. First, consumer subsidies have been widely used across the globe and amounted to $43 billion worldwide in 2022 (International Energy Agency, 2023). The U.S. Inflation Reduction Act (IRA) of 2022 provides consumer subsidies of up to $7,500 per EV for eligible purchases. China provided generous subsidies for EV buyers in the early years but phased them out by the end of 2022. Increase EV adoption due to subsidies implies more experience in battery production, which, in turn, leads to reductions in battery costs and the prices of EVs. The positive "feedback loops" from LBD can therefore magnify the direct effect of consumer subsidies and other supportive policies. Given the global nature of battery supply network, subsidies can also create spillovers across countries through the LBD channel.

Second, the preferential treatment of domestic battery producers has become part of a growing spectrum of industrial policies in recent years. During 2016-2019, the Chinese implemented a whitelist policy where EV subsidies were tied to the battery producers approved by the central

government. The IRA mandates that a certain fraction (in terms of value) of critical minerals and battery components used in the manufacturing of EVs must originate from North America and free trade agreement partners for those models to qualify for consumer subsidies. The broad impacts of local content requirement crucially depend on the size and scope of LBD. If LBD is predominantly within firms (i.e., internal LBD) and occurs among industry leaders, these policies could accelerate LBD by consolidating production in a smaller set of firms. This would result in reduced EV battery prices but may come at the cost of increased market concentration. Conversely, if policies across countries erect regional barriers and redirect production toward domestic (and potentially less efficient) producers, they might slow down global LBD and hinder the further penetration of EVs. The overall impact on both global and domestic EV adoption is ambiguous and necessitates empirical investigation.

This paper takes advantage of a comprehensive database on the global EV and battery industries that have three key components. The first data set consists of annual EV sales from 2013 to 2020 in thirteen countries which collectively accounted for over 95% of global EV sales. The data report sales and vehicle and battery attributes by model by country for both battery EVs (BEVs) and plug-in hybrid EVs (PHEVs). The second data set contains information on battery suppliers including plant location and crucially the list of EV models supplied. The third data set contains financial and non-financial incentives for EV purchases in each country over time. In addition, we have also collected socio-economic variables and household surveys on vehicle ownership across countries.

We develop a structural model of the global EV and EV battery industries featuring bargaining between battery suppliers and EV producers over battery prices as well as downstream EV production and price competition. The purpose of the empirical framework is to estimate the key modeling parameters (e.g., the extent of LBD and bargaining weights) based on observed data patterns in order to conduct counterfactual simulations. There are two key empirical challenges.

First, we do not observe systematic data on battery costs at the firm-level or vehicle-model level, which are proprietary in nature. To address this challenge, we use our structural bargaining model to infer upstream and downstream margins and recover battery costs based on observed vehicle prices and the demand estimation. The estimation of the battery costs is also informed by industry-level battery costs and some firm-level data from industrial reports.

Second, the experience variable (i.e., cumulative production) that captures LBD is potentially endogenous in the relationship between the marginal cost of battery production and experience. This is because efficient firms with favorable production cost shocks are more likely to sell a large quantity and accumulate more experience. We construct an IV for battery supplier experience by exploiting the variation in suppliers' exposure to downstream EV subsidies, which vary over time

and across vehicle models sold in different countries. The intuition is that a supplier selling batteries to a country with more generous EV subsidies will experience a larger increase in its cumulative production than a supplier selling to a country with lower subsidies. If LBD considerations are present, the battery costs for the former supplier will decrease faster than the battery costs for the latter supplier, ceteris paribus. In addition, we also leverage China's whitelist policy which generated arguably exogenous variation in production experience across battery suppliers.

Our empirical analysis delivers four key findings. First, the learning rate is estimated to be 8.6%, suggesting that a doubling of own experience would lead to a reduction of unit production cost by 8.6%. Firms learn nearly 15 times more from an additional unit of their own production than from that of other firms in the same country. While leading battery producers learn primarily from their own experience, small producers mainly learn from others due to their own limited experience. Overall, LBD accounted for about 34.5% of the overall cost reduction from 2013 to 2020.

Second, LBD greatly amplifies the sales impact of EV subsidies through feedback loops: subsidies are estimated to increase sales by 1.29 million units during our data period without considering LBD, but this impact jumps to 3.35 million units when LBD is accounted for. Similarly, the welfare impact of subsidies is also dramatically enhanced by LBD. These findings highlight that ignoring LBD would significantly underestimate the efficacy and cost-effectiveness of supportive government policies that aim to promote EV adoption.

Third, consumer subsidies by one country generate global spillovers through LBD in battery production, but the extent of spillovers hinges critically on the supply chain network. While subsidies from the U.S. give rise to large spillovers to Europe and vice versa because the large overlap in battery suppliers among EV producers from these two regions, the benefit of Chinese subsidies largely remains within China due to the presence of a larger number battery suppliers that mostly supply domestic automakers.

Lastly, China's whitelist policy significantly benefited Chinese battery suppliers, leading to substantial business losses for Korean and Japanese battery producers, which in turn slowed global EV adoption. Crucially, the whitelist policy also inhibited global spillovers in EV adoption and welfare benefits from consumer subsidies. These findings highlight the important tradeoff between protecting local manufacturing and promoting broader EV diffusion that arises from local content requirements.

Our study makes the following three contributions to the literature. It adds to the growing economics literature to understand consumer adoption of EVs (Li et al., 2017a; Li, 2023; Springel, 2019; Muehlegger and Rapson, 2022; Remmy, 2022; Barwick, Kwon, and Li, 2023). While these

studies focus on understanding demand responses to consumer subsidies and the role of charging infrastructure, they do not account for LBD in the analysis and, as a result, could underestimate the longer-term impact of consumer subsidies and other supportive policies on EV adoption. Our study is the first in the literature to quantify LBD in the global EV battery industry and take it into account when assessing the broad impacts of EV policies.

This study also contribute to the literature on LBD that has been documented in a variety of industries (Irwin and Klenow, 1994; Benkard, 2000; Thompson, 2001; Thornton and Thompson, 2001; Benkard, 2004; Ohashi, 2005; Covert and Sweeney, 2022). Except for Covert and Sweeney (2022), all the studies cited above relied on data on input requirements or costs associated with producing a good, but these data are often hard to obtain due to their proprietary nature. Our study develops a new methodology for estimating LBD without data on inputs and production costs. It exploits variations in prices and quantities of final goods (i.e., EVs) and information on the vertical links between final good producers and intermediate input suppliers. The methodology is well suited to estimate LBD in the production of intermediate inputs (i.e. batteries).

This paper is related to studies that analyzes vertical relationships between manufacturers and input suppliers (Horn and Wolinsky, 1988; Chipty and Snyder, 1999; Crawford and Yurukoglu, 2012; Grennan, 2013; Gowrisankaran, Nevo, and Town, 2015; Ho and Lee, 2017; Fan and Yang, 2020). It contributes to that literature by developing a framework that leverages the vertical relationships to study LBD among the upstream suppliers.

2 Data and Descriptive Evidence

2.1 Data Description

The research relies on four comprehensive data sets on global EV and EV battery industries.

EV Sales and Attributes The first data set contains annual EV sales, vehicle attributes, and prices by model for each of the 13 countries that had the largest EV sales from 2013 to 2020. These countries include Austria, Canada, China, France, Germany, Japan, Netherlands, Norway, Spain, Sweden, Switzerland, the UK, and the US, which collectively accounted for 95% of global EV sales during the data period.

Figure 1 shows the trend in EV sales by country/region in Panel (a), and the market share of EVs in the new vehicle market as well as the zero-emissions vehicle (ZEV) target by country in Panel (b). Since the introduction of mass-market EV models in 2010, worldwide passenger EV sales have grown to reach 14.2 million units, or 15.8% of the passenger vehicle market in 2023.

There is a large variation across countries in EV penetration. China became the largest EV market in 2015 and accounted for 59% of global new EV sales in 2023. In terms of the market share in the new vehicle market, Norway has by far the highest share of nearly 90.4% in 2023, while it was 34% in China, 21.4% in Europe, and 9.4% in the US, respectively.

Battery Suppliers The second data set contains information on battery suppliers such as location and production capacity. It also contains information on battery characteristics for each EV model (e.g., battery capacity and battery chemistry) and, crucially, the identity of battery suppliers. This data set allows us to establish the vertical relationships between upstream battery suppliers and downstream EV producers. We construct the experience variable (i.e., cumulative production) for each battery supplier in each year based on the vertical relationship together with data on EV sales.

Figure A1 shows the supply network in 2013 in Panel (a) and in 2020 in Panel (b). The left side of the figure displays the top six battery producers, while the right side reports the top eight EV producers. The thickness of the lines represents the battery sales volume in units. Both EV production and battery manufacturing are concentrated, illustrating a two-sided duopoly market structure. In addition, EV producers often source from multiple battery supplies while battery suppliers sell to multiple EV producers, except for BYD and AESC, which are vertically integrated firms. These features inform our use of a bargaining model to characterize the vertical relationship.

EV Incentives The third data set contains financial and non-financial EV incentives offered in different countries. Consumer subsidies for EV purchases vary across countries and over time. Importantly, there is considerable cross-model variation within a given country and year due to the fact that the amount of subsidies is often based on vehicle attributes. For example, in the U.S., the amount of subsidy that an EV model is eligible for is \$2500+\$415*(kWh-4), with a minimum battery capacity of 4 KWh and a maximum subsidy of \$7500 during out data period.[1] EV subsidies in China are based on vehicle driving range with a notch design (Barwick, Kwon, and Li, 2023). The wedges in EV subsidies serve as a crucial exogenous source of variation in the experience of different battery suppliers, thereby identifying the extent of LBD — the impact of experience on production costs.

Figure A2 reports the average EV subsidy (from the central government) by country during 2013-2020 in Panel (a) and the subsidy design over time in China in Panel (b). Norway has the most generous consumer subsidies, consistent with its high penetration of EVs. China's attribute-based subsidy from the central government was reduced over time and eventually phased out in

[1]The subsidy phases out following a pre-set schedule when the EV manufacturer hits a cap of 200,000 subsidy-qualifying vehicle. By quarter six after the cap was reached, the subsidy is completely phased out for that EV manufacturer (Lohawala, 2023).

2022.

Demographics and Surveys The fourth data set contains socio-economic variables for each country as well as household surveys on vehicle ownership in China, US and France. Information on vehicle ownership links household demographics with vehicle attributes, providing useful moment conditions to identify consumer preference heterogeneity for vehicle demand.

2.2 Descriptive Evidence

Before presenting the descriptive data pattern that used to inform our identification of LBD and policy impacts, we first discuss how LBD arises in the battery production process. Battery packs used in EVs are composed of battery modules which themselves are made up of a large number of battery cells. Battery production has at least three key features that could give rise to LBD.

First, the production process is highly complex and automated with hundreds of parameters to be set. The inter-connected system needs to be constantly fine-tuned and optimized to achieve efficiency. Second, the process is very sensitive in that it has strong requirement on materials purity and the production requires clean-room process standards. Tiny amounts of impurities can cause high scrap and low yield rate.[2] Third, the industry has been undergoing continuous change in terms of advances in new chemistry composition and production techniques, which have important implications on production costs. All these features suggest that production know-how by managers and engineers in the plant gained through experience could help improve production efficiency and reduce scrap, leading to a lower cost.[3]

The estimate of LBD is fundamentally informed by the relationship between production experience and the cost of battery production. In the absence of cost data, we examine the extent to which vehicle prices, a significant portion of which is attributed to battery expenses, are correlated with the production experience of battery suppliers.

Figure 2 shows the relationship between vehicle prices at the model level and the experience of battery supplies for the corresponding vehicle model in binned scatter plots. The unit of analysis is a vehicle model by country by year. Panel (a) depicts the raw data pattern, while Panel (b) shows the residualized plot by partialing out vehicle attributes (horsepower, size, driving range, and the PHEV dummy), country fixed effects, brand fixed effects, and year fixed effects. The size of the dots is

[2] Even the industry leaders struggle with the issue of high scrap rate in the initial stage of production. For example, the Gigafactory built by Tesla and Panasonic in Nevada in 2017 had a scrap rate as high as 80-90% initially as discussed in this article. It takes several years for the scrap rate to be reduced to 15%.

[3] A report by Boston Consulting Group suggests among the 15 stages of cell production, the most common challenges have to do with yield rate/scrap and efficiency/process time. The report suggests that engineers need to rely on experience, rather than physical correlations, to adjust parameters in order to optimize the production process.

proportional to the cumulative subsidies received by the battery supplier for the corresponding EV model.

Panel (a) of Figure 2 shows a slight positive relationship between battery supplier experience and vehicle prices. This could be driven by the fact that high-end EV models (e.g., Tesla model X) source from more experienced battery suppliers (e.g., Panasonic) for their better quality. After controlling for vehicle attributes and a rich set of fixed effects, Panel (b) exhibits a strong and precisely estimated negative relationship, suggesting that vehicle models that source from more experienced battery suppliers charge lower prices. In addition, the plots show that production experience increases with the cumulative subsidy received in the past by the battery supplier (captured by the size of the dots), motivating a key IV strategy for identifying LBD that we discuss below.

Figure A3 provides some suggestive evidence of the impacts of China's whitelist policy from 2016 to 2019, which requires EV models to use government-sanctioned battery suppliers – all of which are Chinese firms – in order to qualify for subsidies. There were six major battery suppliers during this period: two Chinese firms, BYD and CATL, and four non-Chinese firms, AESC and Panasonic from Japan and LG and Samsung from South Korea. Before the policy was enacted, the Chinese suppliers had less experience, and vehicles that used their batteries sold at higher prices relative to the non-Chinese suppliers.

Panel (a) shows the share of EV models sourcing from Chinese battery suppliers separately for EV models sold in China, and those sold elsewhere. As the policy intended, the share of EV models sold in China sourcing from Chinese battery suppliers increased from about 70% to nearly 90% during the policy period. The share dropped once the policy was scrapped. Panel (b) shows that the sales of the top two Chinese battery suppliers that were on the whitelist increased faster than the top four non-Chinese battery suppliers during China's whitelist policy. As BYD and CATL accumulated production experience, the EV models that sourced batteries from BYD and CATL saw a faster reduction in (residualized) vehicle prices relative to the non-Chinese firms, as shown in Panel (c). This is consistent with the pattern in Panel (a): among the EV models sold elsewhere, the share of models sourcing from Chinese battery suppliers increased slightly during the policy period, but more dramatically after the policy. This large increase could be driven by the fast cost reduction among Chinese battery producers and hence improved competitiveness as a result of the policy. While the descriptive evidence presented here is consistent with LBD, there could be other confounding factors at play. The section below outlines a structural model that allows us to better establish the causal evidence on the size and scope of LBD as well as its implications on government policies.