Do EV Adoption Policies Drive Innovation in Energy Storage Technologies? Evidence from the Chinese Market

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January 9, 2025

Abstract

We examine the impact of electric vehicle (EV) adoption policies on innovation in energy storage technologies. Although many countries have implemented such policies, our empirical focus is on China, which has the largest EV market and a substantial volume of energy storage technology patents. Using a novel firm-level patent database covering 2000 to 2021, we estimate a Poisson fixed-effects innovation model to analyze how China's EV adoption policies from 2009 to 2021 influence advancements in storage technologies. Our findings indicate that financing the purchase of EVs alone is insufficient to drive significant innovation in energy storage. However, the addition of complementary policies that promote the development of a robust infrastructure network, such as charging stations, significantly increases the likelihood of energy storage patent applications in China.

JEL Classifications: O30, O43, O44
Keywords: Energy storage, Innovation, Electric vehicles, Technology adoption

1 Introduction

In the last decade, the global focus on reducing emissions and improving energy efficiency has spurred a global effort to shift road transportation from conventional internal combustion engine vehicles to electric vehicles (EVs).[1] For example, China aims for EVs to make up 40% of all new vehicle registrations, ranging from approximately 9 to 10 million vehicles per year [Ministry of Industry and Information Technology, 2017]. Similarly, Germany has set a goal for 40% to 50% of new car registrations to be electric, while the U.S. targets a 50% share of EVs in new auto sales—all by 2030 [Federal Republic of Germany, 2016, U.S. Congress, 2022]. To accelerate this transition, many governments have implemented economic policies to encourage EV production and consumption. One of the most ambitious efforts is China's EV adoption policy, implemented between 2009 and 2021, and aimed at transforming the automobile market and reshaping the infrastructure supporting EVs. Given China's leading position in global EV sales and production, understanding the outcomes of its policies provides valuable insights into the potential for large-scale policy-driven transitions in other markets.

The efficient and sustainable EV use is based in part on advanced energy storage solutions. Advancements in battery technologies have significantly reduced the cost of lithium-ion batteries, which are critical for EVs and renewable energy storage. By 2023, the price of lithium-ion battery packs fell to a record low of $139 per kWh, with even lower prices in China at $126 per kWh — 11% and 20% less than in the U.S. and Europe, respectively [BloombergNEF, 2023]. Global demand for lithium-ion batteries for EVs reached 770 GWh in 2023 [IEA, 2023, 2024]. To further reduce costs and expand deployment, ongoing innovation now focuses on reducing reliance on critical minerals, exemplified by the development of sodium-ion batteries. In April 2023, BYD introduced the first sodium-ion battery-powered car, the BYD Seagull. Given that the advancement of energy storage technologies is pivotal for the efficiency of electric vehicles, we explore how EV adoption policies influence innovation within the transportation sector.

In this study, we examine whether China's EV adoption policies spurred advancements in energy storage technology. Previous research has focused on the effect of economic policies on EV sales while this paper explores the policy effects on further innovation in storage technologies. Specifically, we ask: do the EV adoption policies boost innovation in energy storage technologies? To answer this question, we focus on China's EV adoption policies, including financial incentives (i.e. subsidies and tax incentives) and infrastructure support, driven by the central government between 2009 and 2021. To empirically assess their impact on innovation, we build a novel firm-level patent dataset for China, covering the period from 2000 onward. Using these patent data, we estimate how EV

[1] Over the last decade, China, Germany, and the U.S. have driven most of the growth in EV sales, accounting for 65% of total vehicle sales worldwide and 95% of EV sales in 2023. China leads with 60% of global EV sales, followed by Germany and the U.S., contributing 25% and 10%, respectively [IEA, 2024]. In 2023 alone, EVs comprised 38% of total auto sales in China, 21% in Germany, and 10% in the U.S. [IEA, 2024].

adoption policies directed at consumers influence a firms' probability of applying for a new patent in storage technologies.

We summarize China's EV adoption policies before describing our unique patent dataset. In 2009, China implemented a structured and comprehensive plan to promote EV adoption, initially focusing on incentivizing EV sales in public transportation through tax incentives and subsidies. In 2010, this policy expanded to increase the number of pilot cities eligible for public transportation subsidies and extended the subsidies to include private vehicles as well. In September of 2013, a new policy phase build onto the 2009 and 2010 policies and provided additional subsidies aimed at developing an interconnected EV ecosystem, specifically by supporting the expansion of charging and battery swap stations. This infrastructure was intended to support the seamless integration of EV usage with adequate charging facilities, laying the foundation for sustained EV adoption. Finally, between 2016 and 2020, local governments received further incentives and subsidies to construct charging points (CPs) and charging/swapping power stations (CSPS).

We study innovation by constructing a unique, firm-level patent database for energy storage and green technologies in China, to the best of our knowledge, the first of its kind. Using the ORBIS Intellectual Property dataset, we linked patent applications to firms' headquarters and standardized firm names across regions, which enables a more precise analysis of patent activity by firm. Our dataset spans patent applications from 2000 to 2023 in green and energy storage technologies, identified using the World Intellectual Property Organization's (WIPO) Green Inventory classifications. This comprehensive database includes 3,066,167 patent applications in green technologies, of which 202,011 are specifically related to energy storage technologies. The data reveal a marked growth in innovation within green and storage technologies over the past two decades, particularly from 2010 to 2020, when patent applications in these fields rose from approximately 55,000 to 340,000 per year. Our data also shows a highly fragmented market, characterized by a large number of small, innovative firms. To complement the patent data, we gathered price and economic data from the China Economic Information Center (CEIC) and supplemented these with energy price indices from the China Statistical Yearbook and China Energy Statistical Yearbook. This unique dataset offers a comprehensive view of regional energy prices and economic indicators, facilitating a thorough analysis of the factors influencing innovation in China's green and energy storage sectors.

We estimate a dynamic Poisson fixed-effects innovation model to study whether adoption policies foster patent applications in storage technologies. Our model controls for past innovation, local spillovers, energy prices, as well as time and firm fixed effects. We report our results as incidence rate ratios for more intuitive interpretation; an estimated ratio greater than one for a given variable suggests an increase in the likelihood of patent applications associated with that variable.

Our results highlight the importance of EV adoption policies in encouraging innovation in storage technologies, especially those policies directed at creating and promoting an interconnected ecosystem of EV usage and charging infrastructure. In addition, we find that past innovation by

other firms, i.e. local knowledge spillovers, has a positive and persistent influence on patent activity in the subsequent time periods. This result is in line with prior work that shows the importance of knowledge spillovers on a firm's patenting activity [e.g. Grossman and Helpman, 1991, Jaffe, 1986, Jaffe et al., 1993]. Finally, we explore the role of energy prices and innovation. We find that neither electricity nor fuel prices consistently show a statistically significant impact on promoting innovation activity in our study. This finding contrasts with prior literature, such as Aghion et al. [2016], Crabb and Johnson [2010] and Knittel [2011], that found a strong positive relationship between energy prices and cost-reducing or clean energy patents. While many related studies use an average energy price index as their instrument, electricity and fuel prices in China are heavily regulated and may not accurately reflect true market conditions. The unique structure of China's fragmented and highly competitive storage technology market might also contribute to our result, suggesting that competitive pressures and market dynamics could play a more substantial role in driving patenting activity.

The paper is organized as follows. Next, we describe our data including the EV adoption policies and innovation trends. Section 3 introduces our model and empirical strategy, and Section 4 analyzes the estimation results. Finally, Section 5 concludes the paper.

2 The Chinese EV Market

The EV industry in China has experienced rapid growth in the past decade, driven by government policies, technological advancements, and an expanding industrial base. In this section, we begin by reviewing EV sales data, followed by a discussion of China's regulatory environment and how government initiatives, such as subsidies, have promoted the growth of the EV market. Finally, we describe the construction of our patent dataset in energy storage technologies to proxy for innovation.

2.1 The EV market share

In 2012, the global stock of EVs was approximately 183,700 vehicles. At that time, the U.S. had the largest share at 38%, followed by Japan at 24% and France at 11%. China accounted for just 6.2% of the global EV stock, reflecting the early stage of its EV market development [IEA, 2013]. Since then, through the combined efforts of central and local governments, automobile manufacturers, and supporting industries, China has transformed into the world's largest EV market [Gnann et al., 2018, Wang et al., 2017]. Annual global EV sales, including both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), have grown on average by 60% per year since 2014, reaching 2.1 million units in 2019. By 2023, China's EV sales surpassed 8 million vehicles annually, accounting for more than 38% of all automobile sales in the country.

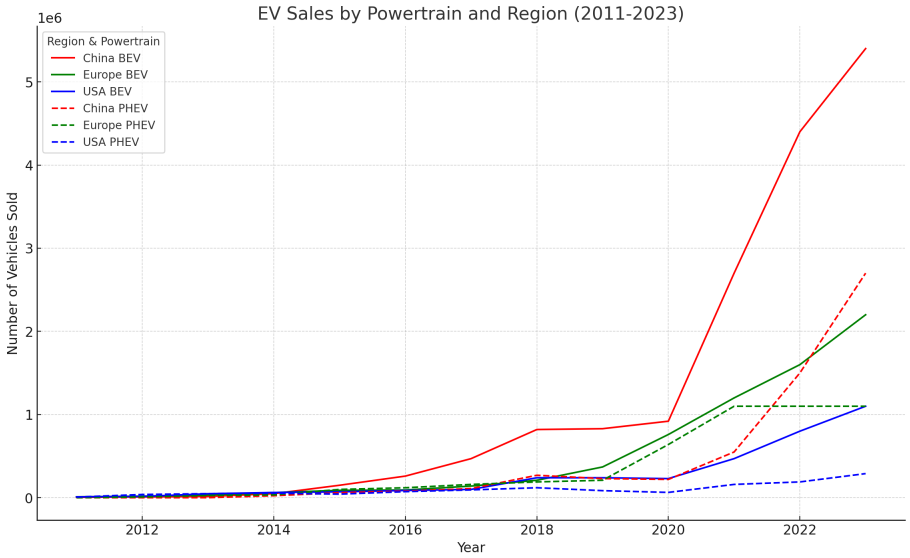


Figure 1: EV sales by powertrain in China, Europe and the US, 2011-2023.

China's EV market is now larger than the combined markets of Europe and the U.S., driven by a high volume of BEV sales [Hertzke et al., 2018]. Figure 1 presents EV sales by powertrain from 2011 to 2023, where EVs refer to the sum of BEVs, which are battery electric vehicles, and PHEVs, which are plug-in hybrid electric vehicles. In 2023, the global EV stock exceeded 40 million vehicles, with China alone holding 21.9 million EVs—nearly double Europe's stock of 11.2 million and more than four times the U.S. stock of 4.8 million [IEA, 2024]. That year, China's share of the global EV fleet reached 54%, underscoring its dominance not only in sales numbers but also in market penetration. For example, EVs accounted for 38% of total auto sales in China in 2023, compared to 21% in Europe and just 10% in the U.S. This rapid market expansion has been supported by targeted government policies, such as subsidies for EV purchases, investments in charging infrastructure, and incentives for domestic EV manufacturing. Figure 2 presents the growth rate of EV sales in China, Europe and the US.

China's leadership in the EV market extends beyond sales figures; it is also the world's largest producer of EVs and the leading supplier of lithium-ion batteries, the technology powering 80% of EVs worldwide. Major domestic manufacturers such as BYD Auto, SAIC Motor, Great Wall Motor, GAC Group, and Geely play pivotal roles in the industry [Zhang et al., 2017]. Additionally, China supplies approximately 70% of global lithium-ion battery demand, thanks to its vertically integrated battery supply chain, which includes the production of EV cells, cathodes, and anodes. This level of consolidation far surpasses that of the U.S. and Europe, making China a dominant exporter and a key player in shaping the global EV market's future [IEA, 2024].

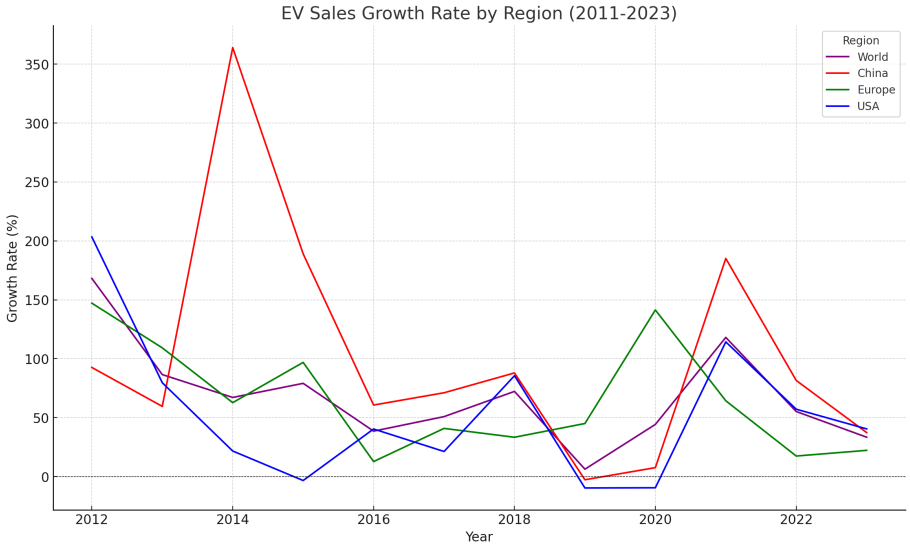


Figure 2: Growth rate of EV sales in China, Europe and the US, 2011-2023.

2.2 EV adoption policies

In the last 20 years, China has implemented many policies to support the sale and use of EVs. These policies can be grouped into three categories: financing the purchase of EVs, promotion of infrastructure to support EVs, and the investment in R&D to advance clean and storage technologies.[2] Out of these three types of policies, the literature that studies innovation in the energy sector has established the positive impact of R&D policies on the development of new technologies (see, for example, Aghion et al. [2016]). Thus, we focus on the first two types of policies: finance policies and infrastructure promotion policies.[3] We summarize these policies in table A appendix A. China's earliest EV policy, named *"The long-term special planning for energy efficiency"*, emphasizes the importance of developing hybrid vehicles (HVs) and exploring EV policies [NDR, 2004]. Between 2004 and 2008, this policy presented a roadmap, whereas, since 2009 a more structured and comprehensive plan has been introduced to accelerate the adoption of electric vehicles by increasing financial support and establishing clear, measurable promotion objectives.

In the first category, the EV finance policy consists mainly of fiscal subsidies and tax incentives. Starting in 2009, the policies provided subsidies for the adoption of electric vehicles in the public

[2] Zhang et al. [2017] provide a comprehensive review of EV policies in China. In addition to providing a review of China's policies, these policies in China relate to EV adoption policies in the US, Japan, and Germany.

[3] "The Energy Conservation and NEVs" and the "Modern Transportation Technology of EV Technology and System Integration" Programs were implemented between 2006 and 2013 to support investments in research and development and advance clean and storage technologies. Additionally, in 2016 the MST initiated a promotion program providing support for R&D efforts on battery technology with the objective of improving the efficiency and safety of batteries for EVs.

sector, specifically for buses and taxis, in 25 pilot cities using a tiered approach. These pilot cities included major metropolitan areas such as Beijing, Shanghai, and Chongqing [Fin, 2009]. This subsidy was directed towards HEVs (Hybrid EVs), PHEVs (Plug-in Hybrid EVs), BEVs (Battery EVs), and FCEV (Fuel Cell EVs) [Hao et al., 2014]. In 2009, approximately half of the subsidies went to HEVs which combine an electric motor/battery assembly with an internal combustion engine. HEVs have a limited electric-only driving range of less than 5 miles because the battery is designed to assist the internal combustion engine rather than to be the primary source of energy. In 2010, an extension policy expanded subsidies to support private sales in 6 cities, including Shanghai and Beijing [MF, 2010]. Eligible brands included major auto manufacturers such as BYD, NIO, XPeng Motors, Li Auto, and SAIC Motor (including its joint ventures with GM and VW), as well as battery leasing companies. From 2013 to 2014, the plan expanded subsidies and tax incentives to 40 cities and city groups. These subsidies supported different engines and electric range capabilities. For example, the subsidy for PHEVs was fixed to those with at least 80Km in electric range. In contrast, the amount of the subsidy for BEVs was based on the electric range: 80Km - 150Km, 150Km - 250Km, and $\geq$ 250Km. The highest incentives were directed to EVs with the most range ($\geq$ 250 Km), usually with higher battery energy density or higher battery capacity [Hao et al., 2014].

In the second category of EV adoption policies, the Ministry of Science and Technology (MST) actively promoted infrastructure development to support EVs at a national level. The infrastructure promotion policy started in 2010 and continued through the years with specific goals around the number of charging poles and power stations. Between 2010 and 2015, the MST proposed the construction of 400,000 charging points (CPs) and 2000 charging/swapping power stations (CSPS) in 20 pilot cities to accelerate transportation electrification [MST, 2012]. The first specialized development guideline for EV infrastructure promotion was issued in 2015, which specifically outlined the construction plan for EV charging infrastructure in 2020 based on demand forecasts[NDR, 2015]. From 2016 to 2020, the Ministry of Finance (MF) provided local governments with subsidies for the construction and operation of charging facilities [MF, 2016a]. In 2020, the MST determined the business model dominated by pure electric drive [MST, 2012].

Finally, from 2016 to 2020, a subsidy phase-out mechanism was introduced at the end of 2016 which specified the conditions for a gradual reduction of subsidies. It established a priority for EVs with higher driving ranges and larger sizes. The phase-out mandated a reduction of 20% in 2019-2020 for all EV subsidies compared to the standards from 2016, with the exception of those for fuel cell vehicles [MF, 2016b]. In 2020, the subsidy reduction was moderated in terms of intensity and pace, with the subsidy standards for 2020-2022 being reduced by 10%, 20%, and 30% respectively [MF, 2020]. This phase-out approach aimed to encourage EV battery technology manufacturers to continue to invest in technological advances that would drive battery cost reductions in order to increase EV commercialization and enable the sustainability of the transition to EVs [Hao et al.,

2014].

In our empirical analysis, we include these policies with dummy variables. Specifically, we generate five dummy variables to control for the existence of specific policies in various cities. These five policies are: (1) the 2009 subsidies to support the adoption of electric vehicles in the public sector across 13 pilot cities (*First subsidy*); (2) the 2010 subsidies in the public sector, which is an expansion of the first subsidy to increase the number of pilot cities to 25 (*Public owners*); (3) the 2010 subsidies to promote the adoption of EVs in the private sector in 6 cities (*Private owners*); (4) the 2013 expansion of subsidies in both the private and public sectors, accompanied by charging infrastructure promotion to create an interconnected ecosystem for EV usage (*Infrastructure*); and (5) the phase-out mechanism (*Last subsidy*).

2.3 Innovation data

Finally, to study innovation, we build a novel patent dataset from the ORBIS Intellectual Property. Specifically, we focus on patent applications filed in China from 2000 to 2023 by domestic and international inventors.[4] The ORBIS Intellectual Property database identifies the current direct owner of each patent application, along with the company's city address and the ultimate parent company. This parent company information allows us to track the ownership of smaller firms, providing a more comprehensive view of innovation activity across both large and small entities. We have firm-level information including location.[5] This harmonization process allows us to standardize entity names across datasets for consistency.

We identify energy storage technologies using International Patent Classification (IPC) codes. Specifically, we follow the World Intellectual Property Organization's (WIPO) IPC Green Inventory, which eases the search of Environmentally Sound Technologies (ESTs).[6] Specifically, we focus on the following storage technologies: fuel cells, hydro energy, hybrid vehicles, charging stations for electric vehicles, storage of electrical energy, and storage of thermal energy. We include the complete list of selected IPC classes in Appendix B. In addition to storage technologies, we also identify green patent applications. We present the patent application breakdown in the Appendix, Table A3.

From 2000 to 2021, there are over 3 million patent applications in green technologies, and 202,011 (around 6.6%) are related to energy storage technologies (see Table **??**). Out of all patent applications in energy storage, 57% are associated with energy conservation. The break-down in Table 1 shows that half of these patent applications represent a form of electrical energy storage.

[4]Patent applications in China often include a patent agency. A domestic individual or firm may apply by themselves or seek the help of a patent agency, however, international inventors without an office in China must employ the help of a patent agency to apply for a patent.

[5]For patents where the current direct owner's city address is missing, we use available address information embedded in company names and performed supplementary searches to identify the city location for most of these firms.

[6]The goal of the Green Inventory is to identify ESTs across a wide range of technical fields.

Table 1: Storage Patent Applications Breakdown, 2000-2021

Storage Patents	Number of Applications
Charging	6,829
Fuel Cells	37,768
Hybrid Vehicles	22,283
Hydro	27,542
Storage Electrical	100,669
Storage Thermal	6,920
Total	202,011

The total number of patent applications in green and energy storage technologies have increased steadily over the 21-year period as seen in Figure 3. From 2000 to 2021, green technology patent applications have grown at an average rate of 21.4% per year, while storage technology patent applications have shown an average annual growth rate of 18.9%.

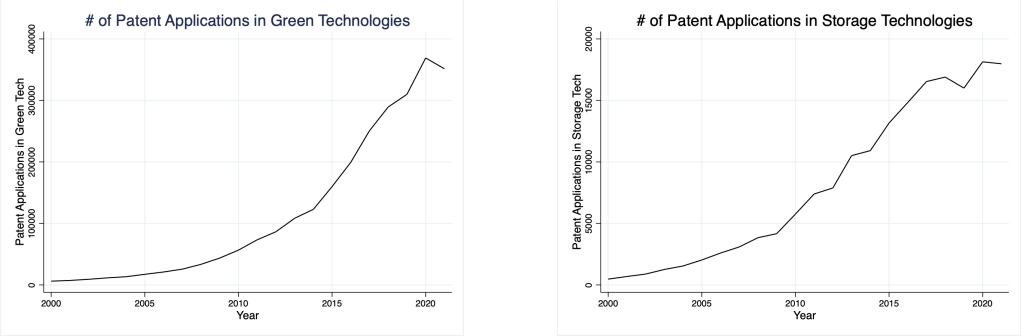


Figure 3: Patent applications in green and storage technologies, 2000 to 2021.

Figure 4 illustrates the share of patent applications in storage technologies relative to the total number of green patent applications, which highlights the dynamic nature of innovation within the green sectors in China. This trend shows a significant increase in the share of storage technology patents from 2000, peaking around 2006, but experiences fluctuations around 2010 and a steady downward trend from 2013 onward. One possible reason is that public and market incentives might have shifted towards other green technologies, such as renewable energy generation.

An interesting aspect of these data is the highly fragmented market in China, dominated by numerous small firms. Figure 5 shows the distribution of firms by the number of patents per firm. Between 2000 and 2021, up to 95% of patent applications in storage technologies were filed by a multitude of small firms. Our data reveal that in China, 68% of total patent applications in storage technologies originated from firms with fewer than two applications over the 21-year

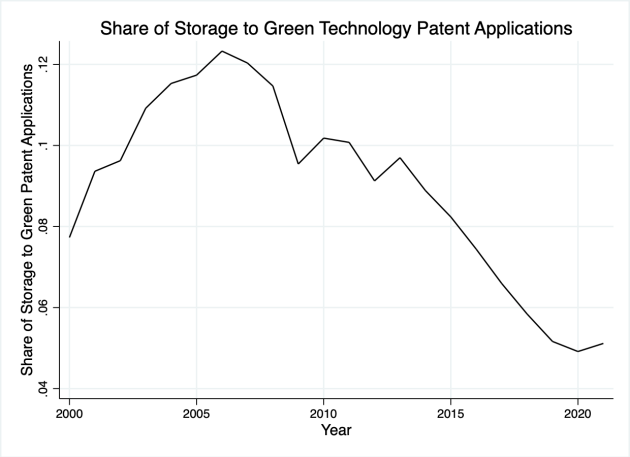


Figure 4: Share of storage patents, 2000 to 2021.

period. In contrast, firms with more than nine applications only accounted for 5% of firms. This environment stands in stark contrast to patent applications in the US, where innovation is often concentrated among the most innovative firms. For example, United States Patent and Trademark Office (USPTO) data from 2000 to 2021 reveals that the top 100 innovators – such as IBM, Samsung, Canon, Microsoft, Intel, Apple, Google, Qualcomm, Sony, LG, and Siemens – each have over 3,500 patent applications, with IBM alone surpassing 100,000 applications during this period [Feng and Lazkano, 2022].

3 EV adoption policies and innovation

In this section, we employ a difference-in-differences (DiD) approach to establish the causal impact of EV adoption policies on energy storage innovation. This preliminary analysis provides a first step in identifying the relationship between these policies and technological advancements, setting the stage for our firm-level analysis in the next section. While we expect that subsidies and tax incentives boost EV sales, the extent to which EV adoption policies drive technological innovation remains less clear. Some may argue that adoption-focused policies may primarily incentivize market expansion rather than directly spurring advancements in supporting technologies such as energy storage. However, the widespread deployment of EVs creates demand for improved battery performance, charging infrastructure, and energy efficiency, potentially fostering innovation in storage technologies. To address this, we conduct a Difference-in-Differences (DID) regression of the five policies described above.

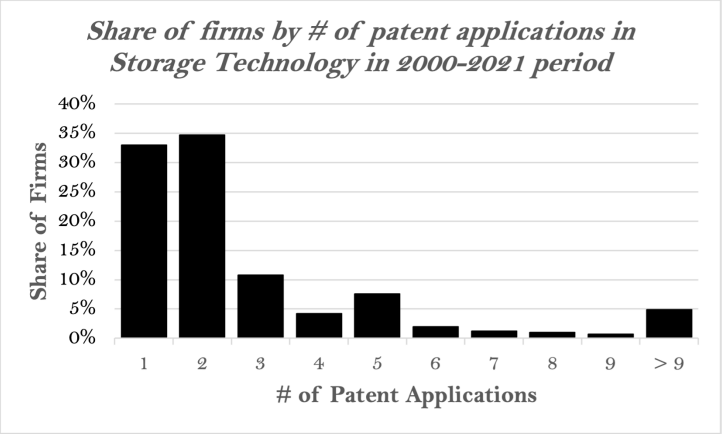


Figure 5: Share of firms by number of patent applications in storage technology, 2000-2021.

Table 2: Individual policy DID results - Marginal effects, 2000-2021

	(b/se)
L.Public09	0.01723
	(0.06722)
L.Public10	-0.05041
	(0.03043)
L.Private10	-0.0452
	(0.02924)
L.Promotion13	0.1696**
	(0.05245)
L.Phaseout	0.1112**
	(0.03682)
N	168,418

Note: Policies are estimated individually
t statistics in parentheses
$^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Our results in Table 2 indicate that neither the 2009 nor the 2010 EV subsidy policies (targeted at the public and private sectors) had an immediate statistically significant effect on patent applications in energy storage technologies. This suggests that, at least in the short term, these policies did not drive advancements in storage technologies. These results are not completely surprising since a large share (close to 50%) of the 2009 subsidies was accounted by HEVs in which batteries

played a minor role. The subsidies from the 2010 private sector policy were targeted at PHEVs and BEVs but it could be the case that due to the early stage of the EV development market in China and a relatively small EV stock, these subsidies were not sufficient to drive innovation activity in storage technologies. We believe that these findings support the idea that additional policy controls were needed to continue to promote the development of the EV market and its commercialization.

In contrast, the 2013 infrastructure development policy and the 2016 phase-out policy both showed immediate and statistically significant effects. Specifically, the 2013 infrastructure policy led to a 16.96% increase in energy storage innovation, underscoring the role of infrastructure investments in advancing technology. Similarly, the 2016 phase-out policy resulted in an 11.12% increase in innovation, suggesting that stricter regulations and a gradual reduction in subsidies can encourage firms to innovate as they look to reduce costs and stay competitive.

These findings highlight the importance of considering both the type and timing of policy measures and not only the adoption of new technology but also its sustainability. While some policies, particularly subsidies, may not show immediate positive impacts, others—such as infrastructure investments and phase-out mechanisms—can significantly stimulate innovation because they represent long term investments and signal the government's commitment to the new technology. This analysis provides a foundation for extending and examining the model further in the following sections, where we assess how these results hold across different models with policy controls.

4 Empirical Strategy

This section describes our econometric approach used to identify the impact of EV adoption policies in firm-level innovation in storage technologies. The innovation literature presents several hypotheses regarding the determinants of innovation in the electricity sector. To empirically evaluate these factors, we employ a dynamic nonlinear model with fixed effects, where current patent applications y_{it} are modeled as a function of market variables, such as prices, the firm's own past patenting activity in year t, and any local knowledge spillovers from other firms. In addition, we incorporate the EV adoption policies detailed in Section 2.2.

The baseline specification for firm i's innovation is estimated as follows:

$$ln(y_{iht}) = A_{iht-1} + \alpha_i ln(P_{it-1}) + \gamma_i Citation_{it} + \mathbf{\Gamma} \cdot \mathbf{Z}_{itp} + \delta_i + \delta_t + \varepsilon_{it} \tag{1}$$

where y_{iht} is the number of patent applications that firm i applies for in year t in technology h (storage or green).[7] P_{it-1} indicates a firm's exposure to the previous year' fuel prices. These

[7]Previous studies, such as Isaksen and Trippl [2017], Parrilli et al. [2020], show that firm-level incentives to innovate often operate regionally. We also follow this approach and assign region to represent the location. Specifically, we use the eight major economic regions defined by the National Bureau of Statistics of China to represent the regions in our study, which exhibit significant disparities in terms of economic development and structural characteristics Zuo et al. [2006].

prices include both electricity and fuel prices, which are common determinants of innovation in the transportation sector.

We include A_{iht-1} which is a firm's existing knowledge stock in technology h. Following Aghion et al. [2016], we define knowledge stock in terms of internal and external past innovations. Specifically, A_{iht-1} is defined by a firm's own stock of patents in technology h accumulated before time t (K_{iht-1}) and the spillovers from all other firms in firm i's region j before time t ($S_{-ijht-1}$). Thus, past knowledge is defined as $A_{iht-1} = \beta_{1j} K_{iht-1} + \beta_{2j} S_{-ijht-1}$.

In addition to the quantity of patents, we account for the quality of firm's past innovations by including the number of citations received by firm i up to year t, $Citations_{it}$. This variable allows us to assess whether the quality of a firm's previous innovations (as indicated by how frequently their patents have been cited) influences their subsequent innovation activity.

Next, the matrix $\mathbf{Z}_{itp}$ represents the effects of multiple EV adoption policies, each with a varying lag structure. As shown in table 2, the difference-in-difference analysis of each individual policy shows that two of the policies are statistically significant at promoting innovation in storage technologies. In our baseline specification, we simultaneously consider all EV adoption policies p that were in effect from 2004 to 2020. Specifically, we include five dummy variables to capture policies implemented during this period. As introduced in Section 2.2, these policies include the 2009 subsidies in the public sector Public09 and its expansion Public10, the 2010 subsidies in the private sector Private10, a structured plan to promote an interconnected ecosystem of EV usage (Promotion13), and the phase-out mechanism (Phaseout). The corresponding vector of coefficients $\mathbf{\Gamma}$ in equation 2 captures the impact of these policies on innovation over time, with each element in $\mathbf{\Gamma}$ representing the weight of a given policy at a specific lag.

$$\mathbf{\Gamma} \cdot \mathbf{Z}_{itp} = \gamma_1 Z^{(1)}_{i,t-1} + \sum_{k=1}^{3} \gamma_2^k Z^{(2)}_{i,t-k} + \sum_{k=1}^{3} \gamma_3^k Z^{(3)}_{i,t-k} + \sum_{k=1}^{3} \gamma_4^k Z^{(4)}_{i,t-k} + \sum_{k=1}^{2} \gamma_5^k Z^{(5)}_{i,t-k} \tag{2}$$

where the summation represents multiple lagged effects. In our estimation results, we present the weight of a given policy taken all lags into account as well as the weight of a given policy at each specific lag. For instance, the second policy (Public10) was implemented in 2010 and substituted in 2013. Thus, for the second policy, γ_2^1 represents the estimated impact of the policy after one year while γ_2^2 and γ_2^3 represent the estimated impact of the policies in each of the next two years. These coefficients represent the marginal effects of the policy for the specific time period. In addition, we calculate the total cumulative effect of a policy over multiple years by taking into account the immediate and the lagged effects together.

Finally, δ_i and δ_t are firm-specific fixed effects that control for unobserved heterogeneity across firms and time fixed effects that capture the influence of year-specific macroeconomic factors, respectively. Lastly, ε_{it} is the error term. We use a Poisson fixed effects estimator and report incidence

rate ratios (IRRs) for ease of interpretation.[8]

5 Results and Discussion

In this section, we present our main estimation results followed by alternative specifications to validate the results.[9] Table 3 presents the year-to-year effects of the five EV adoption policies, while tables 4, 5 and 6 present the cumulative effect of the policies. We also consider alternative prices in table 7.

We highlight two main findings: 1)EV adoption policies have effectively promoted innovation in storage technologies; and 2) past inventions play a crucial role in driving further innovation. In the following subsections we describe these results in detail.

5.1 EV adoption policies

Table 3 presents the year-by-year estimations of various policies on the likelihood of applying for a new storage technology patent. Among EV adoption policies, the 2013 promotion policy stands out and is particularly impactful in driving innovation in storage technologies. This policy provided subsidies associated with vehicle electric range and additional support to expand the charging station network, fostering an interconnected EV ecosystem. In the first year after implementation, the 2013 promotion policy led to a 30% increase in patent applications for energy storage technologies. Although its impact is not significant in the second year, it became positive and significant again in the third year, with a 15% increase in innovation activity. This delayed pattern may reflect an initial boost in innovation due to the policy, followed by an adjustment period during which firms reallocated resources and implemented necessary changes. By the third year, firms had probably adapted to the policy, enabling a more sustained effort in innovation. In contrast, the first three stages of subsidies focused solely on public or private EV adoption didn't demonstrate significant effects on storage innovation. While these policies may have facilitated gradual EV adoption, they fell short of driving advancements in EV batteries because achieving this required a deliberate focus on establishing the support infrastructure necessary for sustaining EVs. As noted by Engel et al. [2018], the lack of charging infrastructure could have posed a significant barrier to EV adoption as consumers purchase increased. Once policies actively supported the development of this infrastructure, battery manufacturers and inventors began to see the potential for investing in research and development and for fostering advancements in more efficient, higher-energy-density batteries tailored to meet the needs of the growing EV market.

[8] IRRs express the change in the rate of an event occurring for a one-unit change in a predictor variable. An incidence rate ratio greater (lower) than one indicates an increase (decrease) in patenting activity. An IRR of one implies no change in storage technology innovation for a one-unit change in the explanatory variable.

[9] Our patent dataset is available to 2023, however, we exclude the last two years of our dataset in our empirical analysis due to the the truncation effects of the data.

In addition, the phase-out policy introduced at the end of 2016 also had a statistically significant impact on storage patent applications in its first year, leading to a 56% increase. However, this impact diminishes in the second year and is no longer statistically significant. This pattern may be attributed to stricter regulations and the gradual removal of subsidies, which likely prompted companies to accelerate innovation efforts initially to capitalize on remaining incentives. However, as subsidies were reduced, the recalculated incentives might not be sufficient to sustain firms' investments in R&D for storage technologies over the longer term.

We then analyze the cumulative effects of these policies in tables 4, 5 and 6. These results are consistent with our findings in table 3, further reinforcing that the 2013 promotion policy and the phase-out mechanism significantly increased the likelihood of new storage patent applications. Our analysis indicates that policies promoting both infrastructure development and vehicle adoption have a lasting impact on the EV industry by fostering innovation. By creating and supporting an interconnected ecosystem of EV usage and charging infrastructure, these policies encourage firms to innovate in complementary technologies like energy storage, driving advancements in battery performance, charging speed, and energy density. In contrast, policies focused solely on public or private EV adoption appear insufficient in driving comparable levels of innovation in storage. This underscores the critical importance of multi-faceted policies that address both consumer demand for EVs and the infrastructure needed to sustain them in the long term.

5.2 Past innovation

Beyond policies, our results highlight the critical role of knowledge spillover between firms, rather than a firm's own past knowledge stock, in shaping continued storage innovation.

Table 3 shows that a firm's own knowledge stock has a significantly negative impact on the likelihood of applying for a storage technology patent after two years (-0.27%), while knowledge spillovers between firms show a significantly positive effect. This positive impact of spillovers remains consistent in tables 4, 5 and 6 with different lag structures, indicating that spillover effects persistently influence patent activity for at least three years. However, a firm's own knowledge stock loses significance over time. The effect of regional knowledge spillovers on innovation is not a surprise and consistent with prior literature [e.g. Audretsch and Feldman, 2004, Jaffe, 1986, Jaffe et al., 1993]. However, the finding that a firm's own knowledge stock in storage technologies does not influence future innovation contrasts with previous literature findings such as Popp [2002]. One possible reason, as discussed above and in Section 2.3, is the highly fragmented nature of the storage innovation market in China, where 95% of storage technology patent applicants filed two or fewer (≤ 2) patents during the 21-year period. This fragmentation may prevent firms from accumulating the focus and resources needed to develop expertise and generate innovative knowledge in emerging storage technologies. This market structure likely explains the lack of statistical significance in

Table 3: Storage Patent Applications Regression - Rate Ratios, 2000-2021

	Patent applications
L2.K stock	.99739*
	(.0013043)
L2.Spillover	1.00002***
	(4.36e-6)
L2.Citations	1.00009
	(0.000281)
L.Public09	1.0275
	(.10821)
L.Public10	1.0356
	(.06916)
L2.Public10	.95982
	(.062683)
L3.Public10	.98099
	(.056488)
L.Private10	1.0109
	(.066476)
L2.Private10	.90389
	(.061562)
L3.Private10	1.0867
	(.066646)
L.Promotion13	1.3012**
	(.13298)
L2.Promotion13	.8582
	(.084294)
L3.Promotion13	1.146**
	(.059262)
L.Phaseout	1.5623***
	(.19768)
L2.Phaseout	.79755
	(.092558)
L.elec.price	.48757
	(.29104)
L2.elec.price	3.3091
	(3.2632)
L3.elec.price	.29654**
	(.12063)
L.fuel.price	.81579
	(.32307)
L2.fuel.price	1.6253
	(1.3879)
L3.fuel.price	.90997
	(.68911)
Observations (N)	166,341

*Note: Prices are inflation adjusted, *p < 0.05, **p < 0.01, ***p < 0.001*

Table 4: Lag 1 Results Storage Patent Applications Regression - Rate Ratios, 2000-2021

	Patent applications
L.K stock	.99846
	(.0010699)
L.Spillover	1.000017***
	(3.55e-06)
L.Citations	1.00002
	(.0002674)
L.Public09	1.029
	(.11424)
L.Public10	1.0019
	(.048778)
L.Private10	.97141
	(.050441)
L.Promotion13	1.2666**
	(.10345)
L.Phaseout	1.4063***
	(.12871)
L.elec.price	.70391
	(.14465)
L.fuel.price	.82579
	(.32038)
_cons	4.9243
	(16.681)
N	168418

*Note: Past polices are replaced by new policies, t statistics in parentheses, *p < 0.05, **p < 0.01, ***p < 0.001*

Table 5: Lag 2 Results Storage Patent Applications Regression - Rate Ratios, 2000-2021

	Patent applications
L2.K stock	.99839
	(.0011938)
L2.Spillover	1.00002***
	(3.38e-06)
L2.Citations	.99999
	(.0002649)
L.Public09	1.0125
	(.10527)
L2.Public10	1.0045
	(.043814)
L2.Private10	.94148
	(.042039)
L2.Promotion13	1.2108**
	(.084699)
L2.Phaseout	1.2162**
	(.088889)
L2.elec.price	1.0122
	(.29031)
L2.fuel.price	1.1822
	(.47757)
_cons	.27277
	(.94564)
N	194868

*Note: Past polices are replaced by new policies, t statistics in parentheses, *p < 0.05, **p < 0.01, ***p < 0.001*

Table 6: Lag 3 Results Storage Patent Applications Regression - Rate Ratios, 2000-2021

	Patent applications
L3.K stock	.99883
	(.0012251)
L3.Spillover	1.000021***
	(3.76e-06)
L3.Citations	.99988
	(.0002393)
L.Public09	.98282
	(.10696)
L3.Public10	1.0385
	(.041523)
L3.Private10	.98149
	(.039936)
L3.Promotion13	1.3238***
	(.079893)
L3.Phaseout	1.2604***
	(.085086)
L3.elec.price	.5599**
	(.10377)
L3.fuel.price	.76825
	(.51228)
_cons	8.7095
	(50.807)
N	193669

*Note: Past polices are replaced by new policies, t statistics in parentheses, *p < 0.05, **p < 0.01, ***p < 0.001*

firms' own past innovations, both in terms of quantity (K stock) and quality (Citations), while accounting for the observed significance in knowledge spillovers. It suggests that, in this context, market structure plays an important role, and thus, knowledge stock alone is not sufficient to drive innovative activity in storage technologies.

5.3 Energy prices

Finally, we focus our attention to energy prices. As shown in table 3, electricity prices do not significantly affect storage innovation for the first two years, but their effect in the third year is negative and statistically significant. Meanwhile, fuel prices do not show a significant effect on innovating activity for storage technologies. One possible explanation for these findings is that electricity and fuel prices are heavily regulated in China, which may prevent them from accurately reflecting true market conditions[Shi and Sun, 2017].

Table 7: Alternative prices results, 2000-2021

	L1	L2	L3
Fuel Retail	0.0001779	-0.0011906	0.0008732
Fuel Purchasing	0.0079505***	0.0078566***	0.0039997**
PPI_Power	-0.0038868	-0.0053433	-0.0121352***
PPI_Coal	0.0045002***	0.004667***	0.0021854**
PPI_Petroleum	0.0038578	0.0000588	-0.0035496*

Note: Price effects are measured with control
t statistics in parentheses
$^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

To further explore this, we consider three alternative price indices sourced from the China Statistical Yearbook and China Energy Statistical Yearbook: (1) the Fuel Retail Price Index (2) the Fuel Purchasing Price Index, and (3) the Producer Price Indices (PPI) for various industries, specifically the Power, Coal and Coking, and Petroleum industries. The PPI and Purchasing Price Indices are available from 2012 to 2021, while the Retail Price Indices are available from 2000 to 2021. We standardize these indices as alternative price measures in different model specifications.

We present these regression results in Table 7, focusing on the first three lags to capture short- and medium-term effects. The Retail Fuel Price Index does not show any statistical significance, suggesting that short- to medium-term fluctuations in retail fuel prices have minimal immediate influence on energy storage patent applications. This result indicates that firms' innovation efforts in energy storage may not be directly responsive to changes in retail fuel prices.

In contrast, the Fuel Purchasing Price Index has a significantly positive effect on storage patenting, with the magnitude of this effect decreasing over successive lags. This positive relationship aligns with innovation theory and prior studies that link energy prices with increased innovation in renewable and efficiency-enhancing technologies [e.g. Feng and Lazkano, 2022, Ley et al., 2016, Newell et al., 1999, Popp, 2002, Verdolini and Galeotti, 2011]. These findings suggest that firms are more likely to intensify research in energy storage in response to rising fuel purchasing prices.

The PPI for the Coal and Coking Industry consistently exhibits a highly significant positive influence on storage technology innovation. Given China's position as the world's largest coal producer and its strong reliance on domestic coal, this positive effect likely reflects the impact of coal price fluctuations on industry dynamics [Zhu et al., 2022]. As domestic coal prices fluctuate, firms may be incentivized to innovate in energy storage technologies to mitigate reliance on coal. Additionally, the PPI for the Power and Petroleum Industries shows highly significant negative impacts on storage patenting in the third year, in line with our baseline findings for electricity prices.

6 Conclusion

The transition to EVs marks a pivotal step in addressing global energy challenges. At the heart of this shift lies the advancement of energy storage technologies, which facilitate the broad adoption of EVs by enhancing battery performance, charging efficiency, and energy density. Public policies are instrumental in accelerating innovation within these areas, especially in high-growth markets like China, where the EV sector has rapidly expanded over the past decade.

Our study examines the impact of China's EV adoption policies from 2009 to 2021 on innovation in energy storage technologies, using firm-level patent data from 2000 to 2023. We find that comprehensive policies integrating infrastructure development with EV adoption, such as the 2013 promotion initiative and the 2016 phase-out mechanism, significantly foster storage-related innovation. These policies act as catalysts to an increase in patent applications for energy storage technologies, underscoring the importance of establishing a supportive ecosystem for transport electrification.

In contrast, the earlier policies that focused solely on incentivizing EV adoption in the public and private sectors show limited direct effects on innovation. This indicates that while adoption incentives are essential, they may not be sufficient to drive technological advancements in energy storage on their own. Infrastructure investments, alongside adoption incentives, appear to be crucial in sustaining meaningful innovation. Our findings also highlight the significant role of knowledge spillovers in China's fragmented innovation landscape, where small firms are highly active in patenting. These spillovers have a more substantial influence on driving new innovations than a firm's own historical research efforts, emphasizing the collective nature of progress in energy

storage technology.

In summary, our results indicate that developing an interconnected ecosystem of EV usage and charging infrastructure is essential for promoting innovation in energy storage technologies. These insights provide valuable lessons for other markets and jurisdictions seeking to stimulate technological progress and accelerate the EV transition. As EV adoption expands globally, fostering both adoption incentives and supportive infrastructure will be crucial to overcoming technological barriers.

Future research could explore the long-term impacts of these policies across different sectors within the clean energy landscape to see if similar frameworks could encourage innovation in other green technologies. Additionally, exploring the adaptability of these policies in various economic contexts and their impact on broader energy transitions may offer further insights into optimizing public policy to support and advance global sustainability goals.

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Appendices

A Description of EV adoption policies in China

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Policy Name	Cities	Policy Summary	Original Policy Name

Table A0 – Continued from previous page

Policy Name	Cities	Policy Summary	Original Policy Name

Continued on next page

Public09 Beijing, Shanghai, Chongqing, Changchun, Dalian, Hangzhou, Jinan, Wuhan, Shenzhen, Hefei, Changsha, Kunming, Nanchang Launch of a pilot program promoting energy-saving and new energy vehicles (NEVs) in public services such as public transport, taxis, government fleets, sanitation, and postal services through financial subsidies. The policy provided up to 50,000 RMB for hybrid vehicles (including plug-in hybrids) based on fuel-saving rates and maximum electric power ratios, and up to 60,000 RMB for pure electric vehicles. Notice on Launching the Pilot Program for Demonstrating and Promoting Energy-Saving and New Energy Vehicles ()

Public10 Tianjin, Haikou, Zhengzhou, Xiamen, Suzhou, Tangshan, Guangzhou, Shenyang, Chengdu, Hohhot, Nantong, Xiangfan Expansion of the 2009 NEV pilot program by adding new cities, which ended in late 2012. Most of the 25 pilot cities were home to major automobile manufacturers, representing over 30% of the country's vehicle ownership. Notice on Expanding the Demonstration and Promotion of Energy-Saving and New Energy Vehicles in Public Service Fields ()

Private10 Shanghai, Changchun, Shenzhen, Hangzhou, Hefei Launch of a subsidy pilot program for private purchases of NEVs, focusing on plug-in hybrids and pure electric cars, with financial support for vehicle purchases and battery leasing, from 2010 to 2012. The subsidy was determined based on battery capacity, offering 3,000 RMB per kWh. The maximum subsidy was 50,000 RMB per plug-in hybrid passenger car and 60,000 RMB per pure electric passenger car. Notice on Launching the Pilot Program for Subsidies for Private Purchases of New Energy Vehicles ()

Promotion13 Beijing, Tianjin, Taiyuan, Jincheng, Dalian, Shanghai, Ningbo, Hefei, Wuhu, Qingdao, Zhengzhou, Xinxiang, Wuhan, Xiangyang, Changzhutan Area, Guangzhou, Shenzhen, Haikou, Chengdu, Chongqing, Kunming, Xi'an, Lanzhou, Hebei Province Cluster, Zhejiang Province Cluster, Fujian Province Cluster, Jiangxi Province Cluster, Guangdong Province Cluster, Inner Mongolia Cluster, Shenyang, Changchun, Harbin, Jiangsu Province Cluster, Zibo, Linyi, Weifang,

Table A1: WIPO Green Inventory Storage IPC codes

WIPO GREEN SUB-TOPICS	IPC
FUEL CELLS	H01M 4/86-4/98,8/00-8/24,12/00-12/08
HYDRO ENERGY	E02B 9/00-9/06 F03B F03C B63H 19/02,19/04 F03G 7/05
HYBRID VEHICLES	B60K 6/00,6/20 B60W 20/00 F16H 3/00-3/78,48/00-48/30
CHARGING STATIONSFOR ELECTRIC VEHICLES	H02J 7/00
STORAGE OFELECTRICAL ENERGY	B60K 6/28 B60W 10/26 H01M 10/44-10/46 H01G 11/00 H02J 3/28,7/00,15/00
STORAGE OFTHERMAL ENERGY	C09K 5/00 F24H 7/00 F28D 20/00,20/02

Liaocheng, Luzhou, Guizhou Province Cluster, Yunnan Province Cluster A NEV promotion campaign from 2013 to 2015 targeting both consumers and local governments, aiming to deploy 336,000 NEVs across 39 promotion clusters and 88 cities. The program included subsidies for purchasing NEVs, with financial incentives for developing charging infrastructure. Subsidies for pure electric vehicles were segmented by driving range, with differentiated support levels based on range categories. Demonstration cities had to meet deployment targets, ensure diverse vehicle brands, and maintain NEVs at least 30% of new public service vehicle purchases, with annual evaluations determining continued eligibility. Notice on Continuing the Promotion and Application of New Energy Vehicles ()

Phase-out Cities previously covered by the 2013 NEV promotion policy Reduction of NEV subsidies from 2016 to 2020, with cities affected by the 2013 NEV promotion policy experiencing greater policy impact. The subsidy reductions aimed to phase out financial incentives by decreasing support by 20% from 2017 to 2018 and by 40% from 2019 to 2020 compared to 2016 levels, encouraging market-driven industry growth and technological advancement. Guiding Opinions of the State Council on Accelerating the Promotion and Application of New Energy Vehicles ()

B IPC Codes for Green and Energy Storage Technologies

Table A2: WIPO Green Inventory

Topic	Sub-topics
ALTERNATIVE ENERGY PRODUCTION	BIO-FUELS INTEGRATED GASIFICATION COMBINED CYCLE (IGCC) ***FUEL CELLS*** PYROLYSIS OR GASIFICATION OF BIOMASS HARNESSING ENERGY FROM MANMADE WASTE ***HYDRO ENERGY*** OCEAN THERMAL ENERGY CONVERSION (OTEC) WIND ENERGY SOLAR ENERGY GEOTHERMAL ENERGY OTHER PRODUCTION OR USE OF HEAT, NOT DERIVED FROM COMBUSTION USING WASTE HEAT DEVICES FOR PRODUCING MECHANICAL POWER FROM MUSCLE ENERGY
TRANSPORTATION	▷ VEHICLES IN GENERAL -***HYBRID VEHICLES, E.G. HYBRID ELECTRIC VEHICLES (HEVS)*** -***CHARGING STATIONS FOR ELECTRIC VEHICLES*** VEHICLES OTHER THAN RAIL VEHICLES RAIL VEHICLES
ENERGY CONSERVATION	MARINE VESSEL PROPULSION COSMONAUTIC VEHICLES USING SOLAR ENERGY ***STORAGE OF ELECTRICAL ENERGY*** POWER SUPPLY CIRCUITRY MEASUREMENT OF ELECTRICITY CONSUMPTION ***STORAGE OF THERMAL ENERGY*** LOW ENERGY LIGHTING
NUCLEAR POWER GENERATION	THERMAL BUILDING INSULATION, IN GENERAL RECOVERING MECHANICAL ENERGY
WASTE MANAGEMENT	NUCLEAR ENGINEERING GAS TURBINE POWER PLANTS USING HEAT SOURCE OF NUCLEAR ORIGIN WASTE DISPOSAL TREATMENT OF WASTE CONSUMING WASTE BY COMBUSTION
AGRICULTURE / FORESTRY	REUSE OF WASTE MATERIALS POLLUTION CONTROL FORESTRY TECHNIQUES ALTERNATIVE IRRIGATION TECHNIQUES
ADMINISTRATIVE, REGULATORY OR DESIGEN ASPECT	PESTICIDE ALTERNATIVES SOIL IMPROVEMENT COMMUTING, E.G., HOV, TELEWORKING, ETC. CARBON/EMISSIONS TRADING, E.G. POLLUTION CREDITS STATIC STRUCTURE DESIGN

C Summary statistics

Table A3 summarizes the breakdown of green patent applications from 2020 to 2023.

Table A3: Green Patent Applications Breakdown, 2000-2021

Green Technologies	Applications in Green Tech	Applications in Storage Tech
Administrative	421,613	0
Agriculture Forestry	103,175	0
Alternative energy	497,402	65,170
Energy Conservation	750,625	114,418
Nuclear	22,409	0
Transportation	208,741	22,423
Waste Management	1,062,202	0
Total	3,066,167	202,011