Global Coordination Challenges in the Transition to Clean Technology: Lessons from Automotive Innovation [*]

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Abstract

Significant progress reconciling economic activities with a stable climate requires radical and rapid technological change in multiple sectors. Here, we study the case of the automotive industry's transition to electric vehicles, which involved choosing between two different technologies: Fuel Cell Electric Vehicles (FCEVs) or Battery Electric Vehicles (BEVs). We know very little about the role that such technological uncertainty plays in shaping the strategies of firms, the efficacy of technological and climate policies, and the speed of technological transitions. Here, we explain that the choice between these two technologies posed a global and multi-sectoral coordination game, due to technological complementarities and the global organization of the industry's markets and supply chains. We use data on patents, supply-chain relationships, and national policies to document historical trends and industry dynamics for these two technologies. While the industry initially focused on fuel cell technologies, around 2008, the technological paradigm shifted to battery electric vehicles. National-level policies had a limited ability to coordinate global players around a type of clean car technology. Instead, exogenous innovation spillovers from outside the automotive sector played a critical role in solving this coordination game in favor of battery electric vehicles. Our results suggest that global and cross-sectoral technology policies may be needed to accelerate low-carbon technological change in other sectors, such as shipping or aviation. This enriches the existing theoretical paradigm, which ignores the scale of interdependencies between technologies and firms.

Keywords: Energy innovation, Industrial policy, Coordination, Electric cars, Fuel cells.

Significance Statement

The transition to low-carbon technologies is an urgent global challenge. While existing recommendations focus on expediting clean technology cost reductions and policy-induced adoption, our research offers a new, complementary perspective. We explain when these transitions can be viewed as global coordination games. Turning to the car industry, we highlight that the choice it had to make between FCEVs and BEVs is an example of such a coordination game. We document an unexpected shift in the industry from an initial focus on FCEVs to BEVs. This shift wasn't driven by national policies but rather by exogenous battery advancements in electronics. Our findings underscore the often-ignored role of cross-sectoral spillovers and provide a rationale for globally coordinated industrial policies.

Introduction

Addressing climate change requires decarbonizing the transportation sector. Currently, Battery Electric Vehicles (BEVs) are in the spotlight, with major car manufacturers setting bold BEV goals, governments investing in charging stations and setting phase-out objectives for Internal Combustion Engines (ICE). However, BEVs aren't the only option. Fuel Cell Electric Vehicles (FCEVs) have been regarded as another promising choice, and for a long time, there was no clear favorite between the two. What then made the industry lean more towards BEVs?

Understanding why the industry favored BEVs is vital for green innovation policy for two main reasons. First, this question leads us to focus on coordination dynamics in transitioning to new technologies in a concrete empirical setting. This is noteworthy because coordination external-

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ities are often cited as justifications for industrial policies[1–3]. Yet, there is little evidence of how coordination affects the transition to green technologies in practice. Second, coordination challenges can lead to protracted periods of technological uncertainty[4], slowing down an industry's shift to net zero. Therefore, understanding how such uncertainty was resolved in the automotive case is essential to guide faster green transitions in the future[5]. Indeed, several hard-to-abate sectors (e.g., shipping) show characteristics similar to the automotive sector, making this case study essential to learn from.

This paper first proposes a theoretical framework predicting the scale of coordination an industry requires to switch to a new technology. According to this framework, carmakers' and policy-makers' choice between FCEVs and BEVs leads to a global multi-sectoral coordination game. These technologies display significant complementarities, particularly with upstream and downstream sectors: FCEVs require a hydrogen supply, while BEVs demand a fast-charging infrastructure. Such complementarities imply that one dominant technology can emerge in the globally integrated market and production network for lightweight vehicles.

As described in the Methods section, we then use patent and supply-chain data to track innovation targeted at FCs and batteries over time for carmakers, their subsidiaries and suppliers, and for actors outside the industry. Our data reveal that carmakers hesitated between these two technologies for a long time, focusing initially on FCs before shifting their focus to batteries. No global institutions ever arose to coordinate actors. Instead, a fortuitous wave of battery innovation from outside the sector, especially from electronics, led the industry and policy-makers to eventually focus on BEVs. Our study, therefore, highlights the importance of learning dynamics in technological transitions[6,7], and especially of cross-sectoral knowledge spillovers[8]. Compared to prior studies[9,10], our study shows the critical role of supply-chain networks in facilitating these spillovers.

Our analysis also examines the role of national innovation policies in steering the industry's choice. We use data on public RD&D funding for hydrogen, fuel cells, and electric storage to capture financial support offered to FCs and battery. We also compile a new dataset on countries' strategic orientations for clean vehicles. Such plans set technological priorities for actors across relevant sectors at the national level, attempting to coordinate them. This is the first study to systematically compile data on this type of policy. We find that pre-2010, they were globally uncoordinated, with different countries pushing for different technologies. It is thus no surprise to find that, prior to 2010, they were unable to lead carmakers' choices.

While there is growing research on the shift to BEVs[11–14], this paper is the first to quantitatively study firms' choice to innovate on FCEVs versus BEVs and to provide an explanation for the industry's eventual shift to BEVs. In doing so, the paper sheds new light on the critical question of how to effectively direct technological change toward cleaner technologies. A clear theoretical paradigm has emerged to answer this question[15–20], buttressed by numerous case studies of the growth of the solar and wind energy sectors[21–23]. In contrast to these well-studied cases, the EV case brings to the fore new issues because it requires long-established companies to adopt entirely new technologies, a situation mirrored by other hard-to-abate sectors. Here, technological interdependencies and coordination dynamics take center stage, which have received little attention in previous work[24,25]. Previous work also ignores the mismatch between the scope of innovation policies, which are often national, and the global structure of production in many sectors[26].

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1 Technological choice as a global coordination game

First, we explain when the transition of an incumbent industry to a new technology displays features of a global coordination game, and we show this is notably true for the transition to clean cars. By "coordination game", we mean a situation where players have multiple clean options. Which of those options maximizes payoffs depends on what others decide. Uncertainty about others' intentions then leads actors to favor the polluting status quo. We propose that two main factors determine the existence of such a game in the transition to a new technology: 1) the degree of technological complementarities and 2) the degree of market integration.

Strong complementarities in technological components. Road transport systems based on FCEVs and BEVs require different sets of complements[27,28] (Figure 1a). FCEVs rely on a combination of a fuel cell and hydrogen storage, while BEVs use batteries. These storage methods influence the car's design and manufacturing processes, needing specific components like cathodes, anodes, and electrolytes. As a result, they each demand unique investments from suppliers. Such low modularity in the design options means that players must work together to ensure their technological advancements are compatible[4,29,30].

Each technology also requires a different upstream energy supply and downstream energy distribution infrastructure. BEVs can initially use the existing grid if sufficient charging infrastructure exists. FCEVs need hydrogen and the infrastructure for its delivery, like pipelines. This means that the technological characteristics of clean cars call for tight collaboration between carmakers and suppliers, as well as other actors in the economy's energy system.

A globally integrated market with shared suppliers. Most carmakers operate in numerous countries (Table A.2) and tap into a shared network of international suppliers (Figure 1b). The network has low modularity, indicating that carmakers are tightly integrated. In fact, half of all carmaker pairs share a supplier. This means there are no clusters of firms operating independently.

These network characteristics reflect a general movement towards the global integration of production, beginning in the 1970s[31] and accelerating in the 1990s[32]. In the car industry, this shift came long after the standardization of the ICE and its parts. This change led to a globalized and vertically disintegrated production process[33], which brought about benefits such as economies of scale and scope and reduced labor costs. Yet, such a network favors incremental innovation on individual components, easily outsourced to the network of global suppliers[34].

When can several technologies co-exist? Figure 1c brings together the two dimensions discussed above to make predictions about the scale of coordination needed to enable investments in a radically new technology. When there's no technological interdependence, firms have the flexibility to explore any technological path. But in the presence of complementarities, coordination becomes essential for a clean option to emerge. Coordination here simply means that firms end up choosing the same technology, without necessarily communicating about it. Coordination can occur when firms react to signals like falling costs or policy shifts, leading to a consensus on a particular technology. If different players are active in different markets (low market integration), local coordination suffices, and different markets can adopt different technologies.

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However, if market integration is high, as we argue it is in the car industry, players must converge on one technology. History offers numerous examples of industries faced with multiple technological options that were incompatible due to their lack of modularity, leading to the dominance of one option[35,36]. In the car industry, technological uncertainty on the choice of FCEVs over BEVs likely reduced the incentives of car manufacturers and suppliers to invest and innovate on related technologies[37]. And, until the direction of technological change became clear, large investments to scale up production and infrastructure were unlikely to materialize.

Our framework poses a puzzle: in the absence of an international institutional process to coordinate technological choice, how did the car industry converge on BEVs? This paper looks at two possible answers: 1) national policies and 2) cross-sectoral spillovers that exogenously provided some of the technological complements depicted in Figure 1a. We rule out a third possible answer: that actors perceived FCEVs to have too many technical or environmental drawbacks relative to BEVs. On the contrary, FCEVs were considered a closer substitute to ICEs due to range and ease of refueling[27]. Many government and industry documents enthusiastically reported rapid fuel cell cost and performance improvements and expected market competitiveness by 2015. In fact, the prevailing view around 2005 was that FCEVs would dominate the long-range vehicle market (representing over 50% of total vehicles), with BEVs catering to short-range compact cars.

Tesla and Hybrid Cars Viewing the shift to clean cars as a global coordination game also helps explain two notable success stories: the development of hybrid vehicles like the Prius and Tesla's pioneering role in the Electric Vehicles (EVs) market. Hybrid vehicles offered a strategy to radically reduce the upstream/downstream complementarities needed to develop EVs (Figure 1c's top quadrants). Early hybrids used batteries with low performance, which were still poorly integrated into the car and didn't require charging infrastructure, but the ICE compensated for this poor performance. Gradually, as the battery and its integration into cars improved, hybrids could rely more heavily on electric propulsion[38]. Tesla, meanwhile, stood out by demonstrating the viability of Li-ion batteries for long-range cars. They did so by targeting the luxury car segment and vertically integrating supply[39], carving out a distinct market niche (Figure 1c's lower left quadrant).

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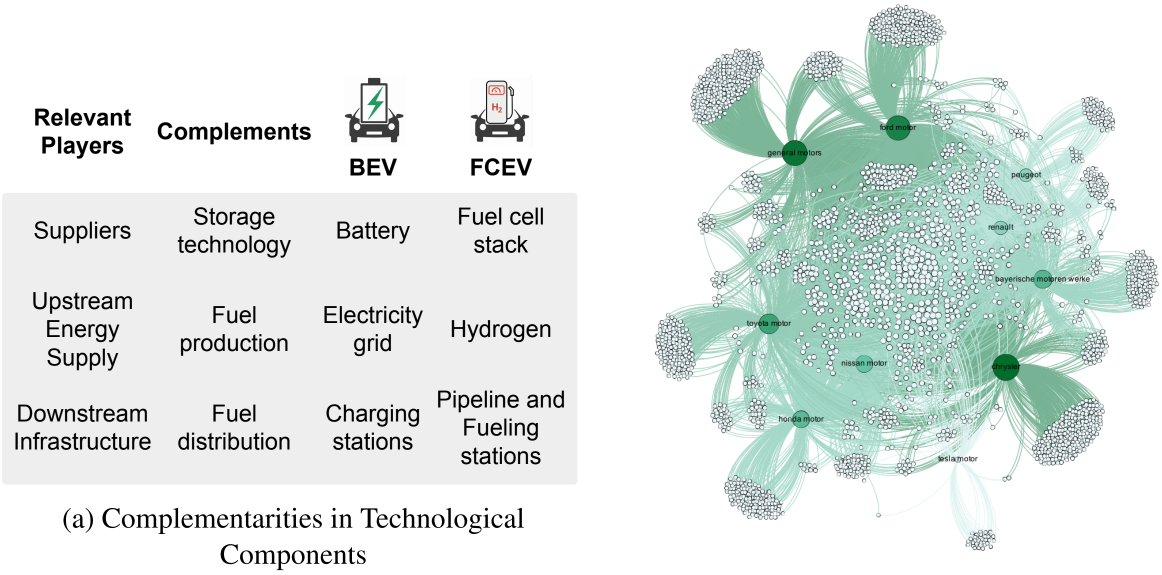
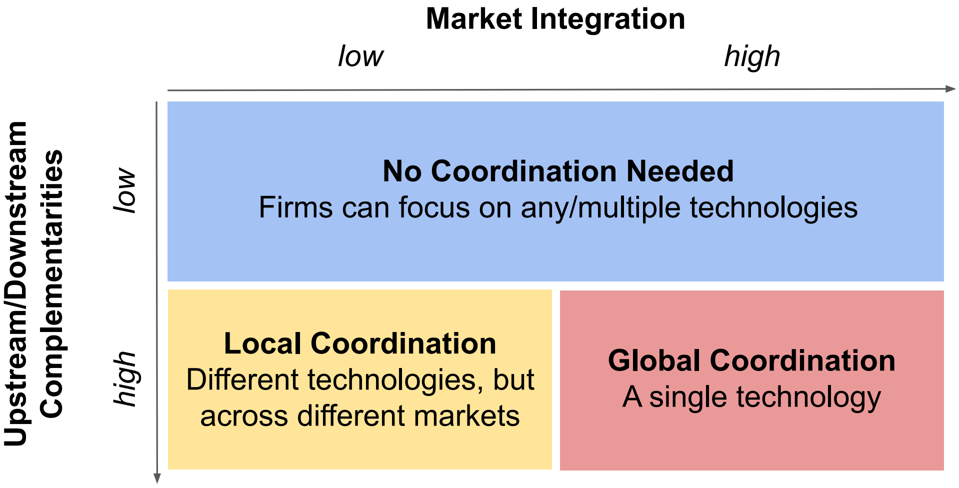


Relevant Players	Complements	BEV	FCEV
Suppliers	Storage technology	Battery	Fuel cell stack
Upstream Energy Supply	Fuel production	Electricity grid	Hydrogen
Downstream Infrastructure	Fuel distribution	Charging stations	Pipeline and Fueling stations

(a) Complementarities in Technological Components

(b) A Tightly Integrated Network of Producers and Suppliers



(c) Industry Characteristics and Need for Coordination.

Note: Figure 1a illustrates that road transport systems based on FCEVs and BEVs require very different sets of complements. Figure 1b shows the global tier-1 supplier network for the ten largest carmakers. Green nodes are carmakers; white nodes are suppliers; their size is proportional to the number of links to carmakers. Figure 1c makes predictions about the scale of coordination needed to enable investments in a radically new technology based on the extent of two critical factors: technological complementarities and the degree of market integration.

Figure 1
Clean Car Development as a Global Coordination Game

2 FCs patenting declined as battery patenting soared.

Our analysis of carmakers' innovation strategies shows that since 1990, patents for clean car technologies have surged, overtaking those for ICEs by 2000 (Supplementary Figure C.1). Yet, a deeper look reveals contrasting trends between FC and battery patenting (Figure 2a).

In the late 1990s, carmakers favored FCs, leading to a swift rise in FC patents until 2004. However, by 2007, FCs experienced a stark "reversal fortune": FC patenting stagnated and sharply declined. Concurrently, battery patenting accelerated. These shifts align with US media's re-

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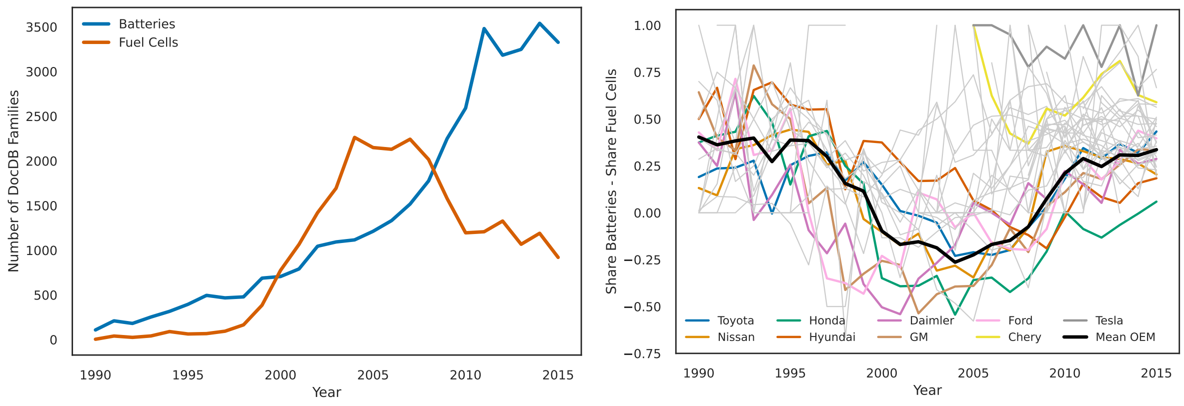
ported cycles of hype and disappointment regarding alternative fuel vehicles: an initial focus on methanol and natural gas, then a hype cycle around BEVs in the mid-1990s, followed by enthusiasm for the hydrogen FCs and biofuels and reverting to BEVs by 2007[12]. This reversal of fortune occurred alongside sustained growth in electric vehicle (EV) patents (Supplementary Figure C.2), emphasizing electric propulsion elements like e-motors and regenerative braking, relevant to both BEVs or FCEVs. While hybrid vehicle patents also increased significantly, they have plateaued since 2008. On the other hand, patents on hydrogen production and distribution, a critical complement to fuel cells, remained sparse.

Remarkably, carmakers' shift from FCs to batteries is globally synchronized: nearly all major carmakers transitioned similarly, first focusing on FC and later on batteries (Figure 2b). While some initiated this change earlier,[1] any lag between followers and leaders didn't exceed five years. Newcomers like Tesla and China's Chery seem to have sidestepped the technological uncertainties incumbents grappled with, entering as the industry was already converging on batteries. Consequently, the industry appears "coordinated," consistent with our earlier arguments that, in a global industry undergoing such a technological shift, companies would converge on the same technology. We see no evidence of modular technological development where firms from different countries pursued alternative solutions.



(a) Fuel Cell and Battery Patenting

(b) Selected carmakers

Figure 2

Carmakers' Patenting Trends: The Decline of Fuel Cells in Favor of Batteries.

Note: Panel 2a plots the number of patent families, filed by at least one carmaker, related to battery or FC technology over time. Panel 2b plots, for each carmaker, the difference between battery and FC patent shares within carmakers' clean car patent portfolio. The carmakers with the most substantial clean car patent output are highlighted, alongside newcomers Tesla and Chery.

3 A lack of policy coordination on FCEVs may have favored BEVs.

From the 1990s, policymakers explored different avenues to promote the development of cleaner cars. Public RD&D funding trends reveal a consistent rise in all countries' investments in FCs from the late 1990s until 2008 (Figure 3b). It then declined, settling at roughly half of its peak

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[1] For example, Daimler pioneered fuel cells in 1994, with GM and Ford following suit. Nissan and Honda's shift, meanwhile, came nearer to 2000.

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value. Conversely, funding for electric storage remained flat until 2008, after which it surged in most countries, notably China.[2]

We then compile and code data on policymakers' *strategic orientation*, frequently outlined in official documents like roadmaps or strategic plans. Strategic orientations outline paths and goals for advancing specific technologies like BEVs or FCEVs and aim at coordinating efforts across national labs, industrial players, and other essential stakeholders, albeit only nationally. Considering our emphasis on coordination dynamics in technological transitions, these strategic policy frameworks could be significant inputs to the policy mix.

Our data reveal that clean vehicle strategic orientations were globally misaligned until 2010 (Figure 3a). Indeed, while national policies attempted to coordinate actors through strategic orientations, these varied across countries, offering no consistent global direction. Yet, by 2010, a global consensus around BEVs emerged, often viewed as a medium-term solution, with some countries contemplating a future shift to FCEVs. The USA, France, and Germany adopted this trajectory in 2008; Asian countries followed in 2010. The UK, in contrast, maintained a technology-neutral strategy for several more years.

We proceed to examine the correlation between firm-level patenting and policies, using measures of policy exposure constructed at the firm level (Figure 3c). This sheds light on the timing of innovation vis-à-vis policy shifts. We also conduct firm-level regressions with the outcome variable being the difference between the proportions of battery and FC patents in carmakers' clean portfolios. This analysis offers a clearer view of the influence of policy timing on firms' focus between battery and FC.

For FCs, we observe that, in the 2000s, carmakers' FC patenting appears to increase at the same time as exposure to FC orientations increases.[3] Yet, public spending on RD&D tends to follow firms' patenting with a lag. Regression analyses support this observation: increased exposure to future RD&D funding for FC (at time $t+1$), and, to a degree, to FC orientation, significantly correlates with a decreased focus on battery relative to FC at time t. This indicates that policies promoting FC likely reacted to corporate decisions rather than directing them.

For battery, around 2008, we observe a synchronous surge in patenting, RD&D funding, and strategic orientations, indicating a shift in strategy by both carmakers and policymakers (Figure 3c). Regression analyses further suggest that firms with greater exposure to battery-specific national orientations in one year focused more on battery patenting the next. This relationship holds when including firm and year fixed effects. Firms exposed to higher public RD&D spending on electric storage the preceding year also focused more on battery patenting. However, this relationship weakens when including firm fixed effects. Thus, the switch of strategic planning and research funding to BEVs coincided and, at the margin, supported the industry's shift to BEVs.

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[2] The USA's significant increase in 2009 is due to the American Recovery and Reinvestment Act.

[3] FC orientations surged in the 2000s, driven by policies in the US, Japan, and Korea.

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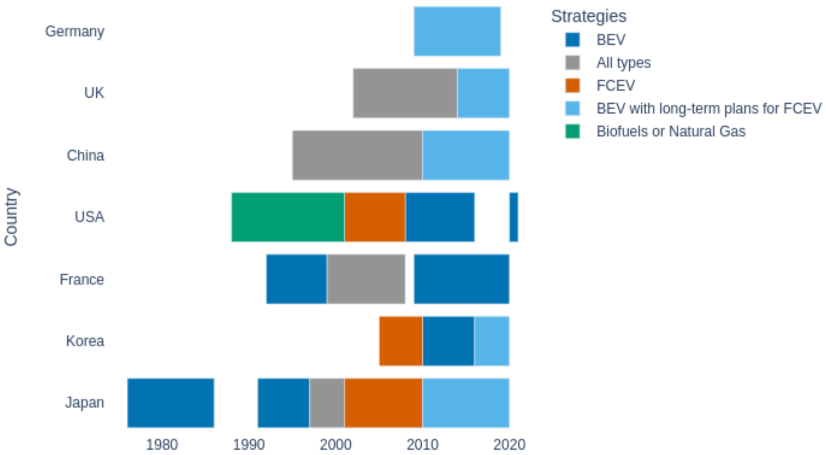
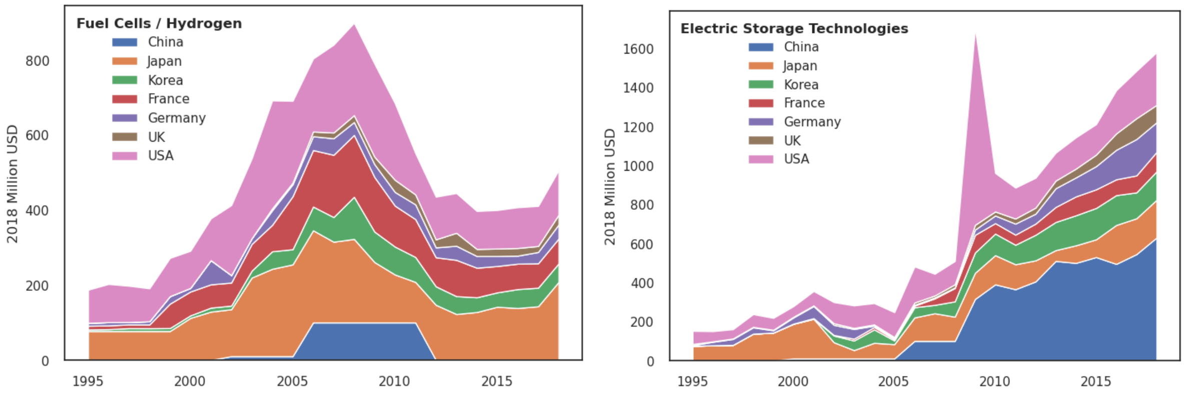
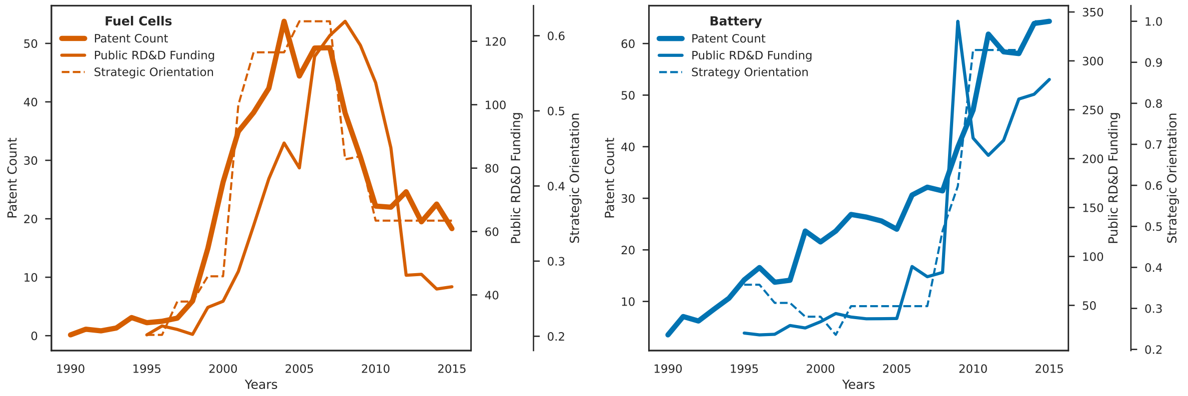


(a) Strategic Orientations for Key Countries Over Time



(b) Public RD&D Funding on Fuel Cells / Hydrogen and Electric Storage Technologies



(c) Trends in Patenting and Policies for the Average Car Manufacturer

Figure 3
Policy Support for Fuel Cells vs. Battery

Note: Figure 3a and 3b display the history of strategic orientations and public RD&D funding related to clean vehicles by country over time. The left panel on Figure 3b shows public RD&D funding for fuel cells and hydrogen, while the right panel shows data for electric energy storage. Figure 3c displays trends in patenting and policy exposure for the average carmaker.

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4 Innovation in batteries originated outside the automotive sector and benefited carmakers through spillovers.

We now turn to the possibility that exogenous innovation spillovers coordinated actors. We extend our dataset to include clean car patents across all economic sectors. We start by examining patents' backward citations to assess the importance of cross-sectoral spillovers. They reveal that carmakers' battery patents predominantly draw upon the knowledge pool outside the industry rather than within (Figure C.4). We find similar results when constructing a measure of *expected* spillovers that adjusts for changes in carmakers' patenting activity[9] (Figure C.5).

We therefore study the patenting trends in other sectors, expecting them to be key influences on carmakers' own innovation. We find that the Motor Vehicle industry—comprising carmakers, subsidiaries, and parts manufacturers—accounts for merely 5 to 15% of all battery-related patents, underscoring the pivotal role of other sectors in pushing battery technologies. The leading other players in battery patenting are industries related to information technologies and electronics (Figure 4a). By the time carmakers accelerated their efforts on batteries circa 2005, these sectors had already been patenting at a high rate for many years, battery performance had dramatically improved, and costs had plummeted tenfold. This suggests that trends exogenous to the car industry created the potential for a technology push toward batteries.

The story for FCs differs considerably. Here, the Motor Vehicle industry takes center stage, accounting for nearly 35% of all FC patents circa 2005, just before the reversal. Other sectors play a more minor role, largely following carmakers' boom-and-bust cycle. Particularly striking is the limited innovation in sectors where FCs and hydrogen exhibit significant potential, such as maritime and air transport and machinery.

Finally, we examine innovation trends among carmakers' "active" suppliers—those with a recorded supply link to any carmaker in year t. Suppliers are pivotal, not just as input providers, but as conduits for cross-sectoral technological spillovers that can eventually benefit a particular technological direction (Figure 4b). Around 2008, we note a sharp uptick in battery patenting among these suppliers, significantly outpacing fuel cells. Importantly, this isn't a shift in existing supplier strategy; instead, it is due to the entry of new firms with experience in battery technology into the supply chain. Indeed, between 2008-2013, carmakers made new relationships with suppliers boasting large stocks of battery patents (Figure 4c). In contrast, these new suppliers' FC patent stocks remained low. Moreover, during the height of FC innovation, we do not observe new relationships with FC-competent suppliers.

This is evidence that cross-sectoral spillovers favoring batteries occurred not just through diffuse knowledge spillovers but also through carmakers' rewiring to battery-competent suppliers from outside the automotive industry. Moreover, this shift coincided with a global alignment of technology policies on batteries and an uptick in carmakers' R&D efforts on batteries. Consequently, the rise of BEVs was facilitated by policy coordination, knowledge flows from related technologies, and complementary knowledge in the supply chain. These conditions did not align with FCs.

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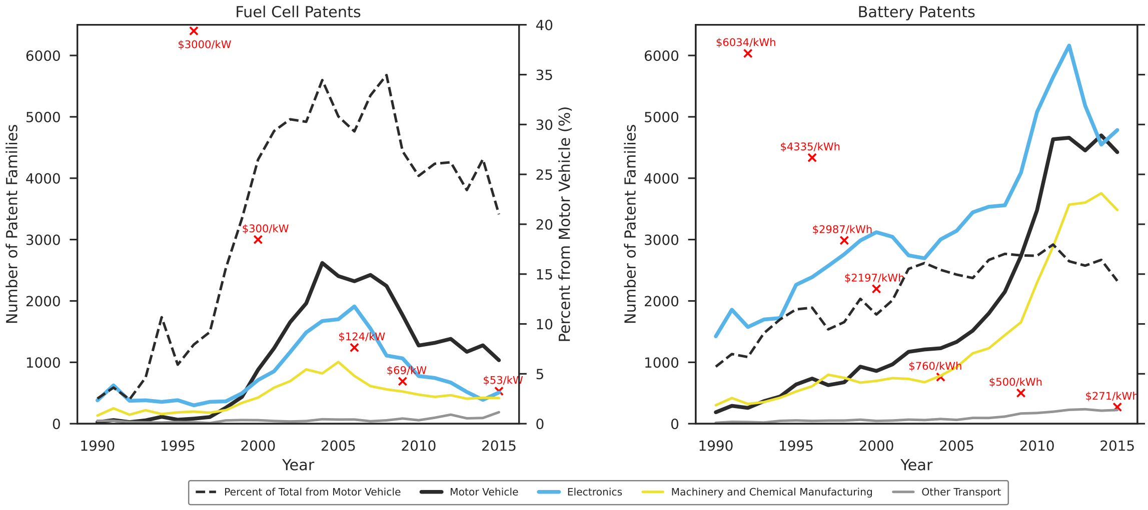
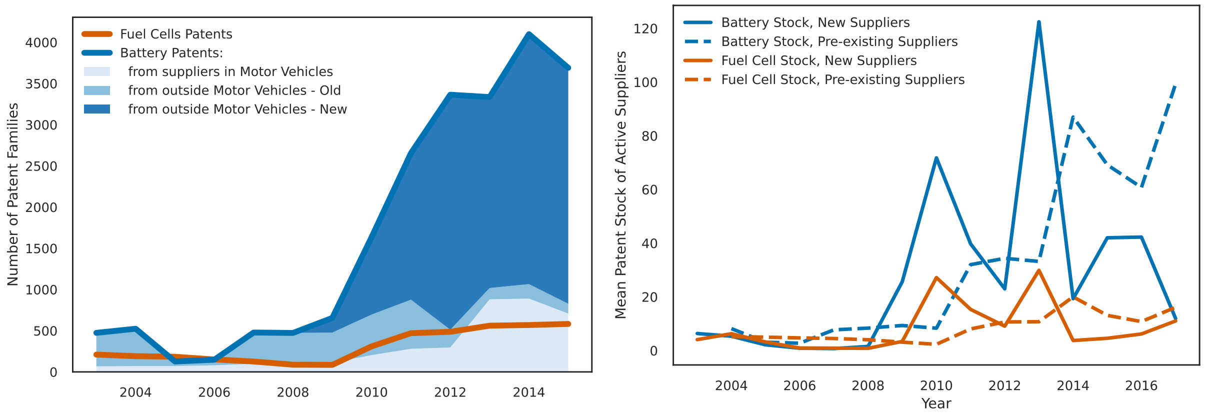


(a) Fuel Cell and Battery Patenting Outside of the Motor Vehicle Industry



(b) Patent Counts of Active Suppliers

(c) Patent Stocks of Active Suppliers

Figure 4
Cross-sectoral Spillovers and Greening of the Supply Chain

Note: The figures illustrate the role and importance of cross-sectoral spillovers for innovation on FCs and battery technologies. Figure 4a overlays patenting trends outside the car industry and information on the evolution of FCs and battery costs over time. We classify patents according to the industry of the filing firm. Figure 4b examines patenting trends for "active" suppliers–those with a documented supply relationship with a carmaker in year t. Figure 4c, on the other hand, shows the average stock of battery and FC patents for pre-existing suppliers and new suppliers, i.e., suppliers that form a link to a carmaker which was not observed before.

Discussion

Our study shows that for two decades, car manufacturers grappled with substantial technological uncertainty. Initially, they leaned towards FCs, only to eventually converge on BEVs. We argue that these innovation strategies reflect a broader global coordination game. Several pivotal observations substantiate this interpretation.

Our data reveal that carmakers move synchronously rather than pursue distinct technological innovation trajectories in regional markets. Moreover, only when policies globally align to favor BEVs do trailing carmakers and traditional suppliers intensify their efforts toward clean cars. Most critically, there is no significant investment in infrastructure and car production before the technological uncertainty is resolved (See Figure E.1). This suggests that without coordination, a protracted period of technological uncertainty can slow down the transition.

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Despite the lack of coordination prior to 2010, both the industry and policymakers eventually converged on BEVs. Yet, this consensus was not a premeditated strategy. Instead, it serendipitously emerged from cross-sectoral spillovers, a byproduct of billions of consumers buying smartphones and laptops. Conversely, the failure of FCs to gain traction can be attributed to several factors: inconsistent policies across markets, inadequate sectoral coordination with upstream hydrogen supply, and an absence of collaboration with sectors that could have concurrently advanced fuel cells, generating broader knowledge spillovers.

The theoretical framework we propose also helps make predictions about the challenges of decarbonizing other sectors. Indeed, industries like shipping, aviation, freight, steel, and cement bear resemblances to the automotive industry. They are considering a range of low-carbon options[40], exhibit interdependencies between upstream and downstream processes, and operate within globally integrated markets.

The main takeaway is that the need for complementary innovations and investments may justify an institutional process to coordinate on a technology. In particular, once sufficient experimentation has established confidence in a technology's potential, policy intervention may be needed to coordinate actors around specific technologies, forming coalitions spanning major markets. Otherwise, it might take an extended period for consensus to form[12]; convergence may also hinge on serendipitous technological advancements that give a distinct advantage to one option over others. The market then becomes the primary arbiter, selecting the most viable option based on market readiness.

But being market-ready doesn't necessarily mean the technology is "best" from a whole-system, long-term perspective, a point long emphasized by scholars focused on technological path dependence[41,42]. For instance, some believe that hydrogen, currently seen as necessary for decarbonizing several industries, could eventually outperform batteries in cars[43]. While our findings highlight the need for global coordination to hasten the shift to clean technology, we also warn of potential pitfalls—primarily, the risk of backing technologies that may prove sub-optimal in the long run.

If industry leaders and policymakers choose to establish institutions favoring specific technologies, two lessons from the auto industry stand out. First is the crucial role of cross-sectoral complements and learning spillovers in allowing new technologies to take off[10,44]. Identifying complementarities and encouraging innovation across sectors should be more fruitful than sectorally isolated innovation programs. Second, inducing technological change through national policies alone is challenging in global industries. Our study thus substantiates recent calls for global sectoral climate-technology agreements to address the urgent need to reduce technological uncertainties and foster accelerated investments in decarbonization[45–48].

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Methods

Sample of Car Manufacturers and Suppliers. We compile a list of car manufacturers from Marklines, an automotive industry portal. We identify 71 firms and matched them to Orbis identifiers (BvD ID) by name. Using Marklines, we gathered sales data by carmaker, year, and country. See Online Appendix Section A for details.

Carmakers often have complex corporate structures due to multiple subsidiaries. Using Marklines data, we group brands under their primary owner. For example, the GM group includes not just GM brands but also Opel and Vauxhall, and while Renault covers Dacia and AvtoVAZ, it doesn't include Renault Trucks, which joined Volvo Group in 2001. To capture all possible subsidiaries, we track the BvD IDs of all the subsidiaries connected to our sample of carmakers, reflecting changes in ownership structure over time.

Suppliers of Carmakers. We use Factset Revere to obtain data on carmakers' supplier-buyer relationships from 2003 to 2017. We match carmakers to Factset by name, extract all suppliers' identifiers, and match them to Orbis by name. The carmakers-supplier network's modularity is notably low at m = 0.3. See Supplementary Table A.3 for details.

Patenting of Car Manufacturers and Suppliers. We collect patent information for these firms using PATSTAT Global Spring Edition 2022, linking patent identifiers and BvD IDs via Orbis IP. We aggregate patent information such that patents filed by any subsidiary are attributed to their parent carmaker's patent activity.

We use CPC and IPC codes to identify patents related to "Clean Car" technologies: batteries, fuel cells, hybrid vehicles, electric vehicles, hydrogen, energy storage, and biofuels. We've refined and updated the code list from previous studies[8,49–51] (See Supplementary Section B).

We aggregate patent applications at the level of DOCDB patent families, which group patents covering the same technical content and, thus, the same invention. This prevents double-counting inventions.[4] We assign dates to these families based on their priority year, which is the year when the earliest application within the family was filed.

We also construct proxies of firm-level knowledge stocks by calculating the cumulative discounted sum of families since 1980. We discount stocks by 15% each year following prior work[52].

Patent citations. From PATSTAT, we compile data on patent citations, noting both the citing and cited patents. Specifically, we categorize these citations by their technology type (like battery) and affiliated firm (such as carmaker or non-carmaker). Following prior work, we use patent citations as a proxy for knowledge spillovers[53]. We also compute a measure of *expected* spillovers which, unlike the basic counts of citations, adjusts for contemporaneous changes in carmakers' patenting activity[9]. For technology k in year t, this is computed as:

$$\hat{S}_{k,t} = \sum_{a=1}^{10} \frac{Citation_{k,a}^{OEM \Rightarrow non-OEM}}{Patents_{k}^{non-OEM}} Patents_{k,t-a}^{non-OEM} \tag{1}$$

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[4] Often, multiple patents are filed for a single invention due to variations in claims or filings across different countries.

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where $Citation_{k,a}^{OEM \Rightarrow non-OEM}$ is the number of citations made by carmakers to non-carmakers regarding technology k with a years of lag (Supplementary Note C.3).

Other Firms Patenting in Battery and Fuel Cell. We use Orbis to obtain the 4-digit NAICS codes for firms patenting in transportation. This lets us classify firms into categories: "Motor Vehicle" (NAICS codes 3361, 3362, or 3363) includes car manufacturers, their subsidiaries and suppliers; "Electronics" combines NAICS 334 ("Computer and Electronic Product Manufacturing") and NAICS 335 ("Electrical Equipment, Appliance, and Component Manufacturing category"); "Machinery and Chemical Manufacturing" (NAICS 333 and 325); "Education and R&D" (NAICS 611 and 541); "Other Transport" (NAICS 336 except Motor Vehicle).

Policy variables. We center our analysis on RD&D support and strategic orientations, as they are technology-push policies that intentionally target certain technologies. Conversely, we exclude demand-pull policies such as consumer subsidies or emission standards due to their technology-neutral aims.

We obtain public energy RD&D funding data from the IEA[54]; it provides data on hydrogen and electric storage funding for all countries, excluding China, from 2004-2018. Data for China was obtained from Zhang *et al.*[55]. Through archival research, we've extended the dataset to cover from 1995 onwards for each country and any remaining gaps in the IEA data.

To assemble a dataset on strategic orientations, we identified the principal policy documents addressing road transport strategy for each period and country (See Supplementary Section D.1). An example is the National Energy Policy by President Bush in 2001, which distinctly lays out technological priorities for each energy sector. We then coded them based on their targeted technology or if they maintained a technology-neutral stance.

We construct country-level measures by numerically coding strategic orientations as follows. Specifically, in year t: A clear strategic focus on technology x is coded as 1; No focus on technology x is coded as 0; If technology x is targeted but without prioritizing it, we code this as 0.5. For example, in China, the strategic orientation score for batteries is 1 because the government gave clear targets for developing BEVs in the short term, and it is 0.5 for fuel cells because of long-term plans for their integration in transport.

For both RD&D funding and strategic orientations, we calculate a firm's exposure using a weighted average of national policies. The weighting is determined by the firm's 2004 sales share in each country.[5].

We then employ a series of regression analyses to delve deeper into the policy-patenting relationship. Results are shown in Supplementary Subsection D.2.

Data Availability

Certain data in this study come from custom datasets purchased from Marklines, Factset Revere, PATSTAT, and Orbis IP. Due to licensing terms, we are precluded from publicly sharing data related to individual observations. However, aggregate counts derived from this data, as showcased in 2, 3 and 4 will be accessible. Data on public RD&D support is freely available

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[5] Ideally, we would use data from 1995, but it is unavailable before 2004.

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via the International Energy Agency[54]. We compiled additional observations, which we will make available. Country-year data on strategic orientation will be made available.

Code Availability

All code involved in data processing, analysis, and figure generation will be made publicly available.

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Competing Interest Declaration

The authors declare no competing interests.

Supporting Online Information

Supplementary Information is available for this paper.

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FOR ONLINE PUBLICATION

Online Supplementary Material

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Global Coordination Challenges in the Transition to Clean Technology: Lessons from Automotive Innovation

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A SAMPLE OF CAR MANUFACTURERS AND SUPPLIERS

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Table A.1
List of Carmakers in Sample

Carmaker ID	Markline Name	Orbis Name
1	Anhui Jianghuai Automotive Group	Anhui Jianghuai Automobile Group Corp., Ltd.
2	Aston Martin	Aston Martin Holdings (Uk) Limited
3	AvtoVAZ	Joint Stock Company ”Avtovaz’
4	BMW Group	Bayerische Motoren Werke Aktiengesellschaft
5	BYD Auto	Byd Auto Co., Ltd.
6	Chrysler Group	Fca Us Llc
7	Changan/Chana (Changan Automobile (Group))	China Changan Automobile Group Co., Ltd.
8	Chery Automobile	Chery Automobile Co., Ltd.
9	China National Heavy Duty Truck Group	China National Heavy Duty Truck Group Co., Ltd.
10	Daewoo Bus Corporation	Zyle Daewoo Bus Corporation Zyle Daewoo Commercial Vehicle Company
11	Guilin Daewoo Bus	Guilin Daewoo Bus Co., Ltd.
12	Daimler Group	Daimler Ag
13	Dongfeng (Dongfeng Motor Corp.)	Dongfeng Automobile Co., Ltd. Dongfeng Motor Co., Ltd. Dongfeng Motor Group Co., Ltd. Dongfeng Motor Group Company
14	FAW (China FAW Group Corp.)	China Faw Group Co., Ltd. Faw Jiefang Automotive Co., Ltd.
15	FCA	Fca Italy S.P.A., In Forma Estesa Fiat Chrysler Automobiles Italy S.P.A. Fiat Chrysler Automobiles N.V. Fiat Spa
16	Ford Group	Ford Motor Co Volvo Car Ab
17	GAZ Group	Gaz Jsc
18	GM Group	Adam Opel Gmbh General Motors Company
19	Geely Holding Group	Volvo Car Ab Zhejiang Geely Holding Group Co., Ltd. Zhejiang Geely New Energy Commercial Vehicles Group Co., Ltd. Zhejiang Haoqing Automobile Manufacturing Co., Ltd.
20	Great Wall Motor Company Ltd. (GWM)	Great Wall Motor Company Limited
21	Guangzhou Automobile Group	Guangzhou Automobile Group Co., Ltd. Guangzhou Automobile Industry Group Co., Ltd
22	Haima Automobile Group	Haima Automobile Company Limited
23	Hawtai (Huatai) Automobile Group	Huatai Automobile Group Co., Ltd.
24	Hebei Zhongxing Automobile Mfg.	Hebei Zhongxing Automobile Co., Ltd.
25	Hinduja Group	Hinduja Automotive Limited
26	Hindustan Motors	Hindustan Motors Limited
27	Honda	Honda Motor Co.,Ltd.
28	Hyundai Kia Automotive Group	Hyundai Motor Co.,Ltd.
29	Iran Khodro (IKCO)	Iran Khodro Industrial Group Company Public Joint Stock
30	Isuzu	Isuzu Motors Limited
31	Jiangling Motors Co. Group	Jiangling Motors Corporation, Ltd.
32	KAMAZ Group	Kamaz Jsc
33	Lifan Technology (Group)	Lifan Industry (Group) Co., Ltd.
34	Mahindra & Mahindra	Mahindra And Mahindra Limited
35	Mazda	Mazda Motor Corporation
36	Mitsubishi	Mitsubishi Motors Corporation
37	Navistar	Navistar International Corp
38	PSA	Peugeot
39	Paccar	Paccar Inc
40	Perodua	Perusahaan Otomobil Kedua Sdn Bhd
41	Porsche	Dr. Ing. H.C. F. Porsche Aktiengesellschaft
42	Proton	Proton Holdings Berhad
43	Qingling Motors (Group)	Qingling Auto (Group) Co., Ltd.
44	Renault	Renault Renault
45	SAIC (Shanghai Automotive Industry Corporation (Group))	Saic Motor Corporation Limited Shanghai Automotive Industry Corporation (Group)
46	Shaanxi Automobile Group	Shaanxi Automobile Group Co., Ltd. Shaanxi Automobile Holding Group Co., Ltd.
47	Sollers Group	Sollers Jsc
48	Subaru	Subaru Corporation
49	Suzuki	Suzuki Motor Corporation
50	Tata Group	Jaguar Land Rover Automotive Plc Tata Motors Limited
51	Tesla	Tesla, Inc.
52	Toyota Group	Toyota Motor Corporation.
53	VDL Group	Vdl Groep B.V.
54	VW Group	Audi Aktiengesellschaft Scania Aktiebolag Volkswagen Aktiengesellschaft
55	Volvo Trucks Group	Aktiebolaget Volvo
56	Xiamen King Long Motor Group	Xiamen King Long Motor Group Co., Ltd.
57	Yulon Group	Yulon Motor Co., Ltd.
58	Yutong Bus Group	Zhengzhou Yutong Group Co., Ltd.
59	Zotye Holding Group	Zotye Holding Group Co., Ltd.
60	CNH Industrial Fiat Industrial	Cnh Industrial N.V. Fiat Industrial S.P.A.
61	Jiangling Motors Co. Group	Jiangling Motors Corporation Limited
62	BAIC Group	Baic Motor Corporation Ltd.
63	Eicher Group	Eicher Motors Limited
64	Force Motors	Force Motors Limited
65	Fujian Motor Industry Group Co. (FJMG)	Fujian Motor Industry Group Co., Ltd.
66	Brilliance Automobile Group	Huachen Automotive Group Holdings Co., Ltd.
67	Nanjing automobile	Nanjing Automobile (Group) Corporation
68	Nissan	Nissan Motor Co.,Ltd.
69	Qoros Auto	Qoros Automotive Co., Ltd.
70	Hualing Xingma Automobile (CAMC)	Hanma Technology Group Co.,Ltd
71	Ford Otomotiv	Ford Otomotiv Sanayi Anonim Sirketi

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Table A.2
Carmakers Summary Statistics for Country Sales

Carmaker ID	Name	Mean Annual Sales	Geographic Concentration	Mean Number of Countries	Mean Nbr Countries with 50%	Mean Nbr Countries with 80%	Nbr Countries in 2004	Nbr Countries in 2018
18	GM Group	8,683,251	0.20	47.29	2	8	31	49
52	Toyota Group	8,518,115	0.14	51.82	2	12	31	61
54	VW Group	7,902,643	0.13	47.71	3	12	30	53
16	Ford Group	5,611,336	0.21	50.12	2	10	31	59
28	Hyundai Kia Automotive Group	5,545,649	0.11	50.18	3	12	28	60
27	Honda	4,071,506	0.20	50.76	2	6	30	59
68	Nissan	3,831,829	0.14	49.71	3	11	28	60
15	FCA	3,539,823	0.23	45.82	2	6	28	53
38	PSA	2,997,508	0.10	44.76	4	10	25	53
6	Chrysler Group	2,534,384	0.65	30.80	1	2	25	
49	Suzuki	2,391,608	0.26	47.88	2	5	27	55
44	Renault	2,285,600	0.10	41.94	5	13	23	52
12	Daimler Group	2,047,411	0.10	48.94	4	12	30	55
4	BMW Group	1,668,659	0.10	46.41	4	11	28	52
35	Mazda	1,282,668	0.11	46.06	3	11	28	55
7	Changan/Chana	993,954	0.94	8.24	1	1	1	8
36	Mitsubishi	949,730	0.06	49.94	6	14	29	59
19	Geely Holding Group	930,539	0.36	33.59	1	6	1	55
13	Dongfeng (Dongfeng Motor Corp.)	833,026	0.96	10.24	1	1	1	12
62	BAIC Group	822,977	0.97	10.88	1	1	1	15
50	Tata Group	813,454	0.37	40.76	1	4	7	56
48	Subaru	730,089	0.36	41.88	1	3	22	50
14	FAW (China FAW Group Corp.)	645,400	0.97	5.41	1	1	1	6
20	Great Wall Motor Company Ltd. (GWM)	605,416	0.89	11.00	1	1	1	11
8	Chery Automobile	535,783	0.74	12.94	1	1	2	10
3	AvtoVAZ	518,455	0.83	14.36	1	1	10	
1	Anhui Jianghuai Automotive Group	405,305	0.84	7.94	1	1	1	12
34	Mahindra & Mahindra	393,492	0.53	24.76	1	2	3	34
45	SAIC	376,961	0.44	20.82	1	3	20	16
30	Isuzu	359,062	0.20	32.94	2	7	16	43
5	BYD Auto	354,809	0.93	6.35	1	1	1	10
66	Brilliance Automobile Group	351,553	0.94	6.94	1	1	1	10
31	Jiangling Motors Co. Group	220,769	0.98	6.00	1	1	1	7
40	Perodua	186,799	0.99	2.88	1	1	3	2
29	Iran Khodro (IKCO)	183,821	0.97	2.10	1	1		
9	China National Heavy Duty Truck Group	183,606	1.00	1.00	1	1	1	1
21	Guangzhou Automobile Group	169,364	0.95	3.24	1	1	1	3
33	Lifan Technology (Group)	149,430	0.64	5.53	1	2	1	6
42	Proton	145,310	0.60	13.82	1	2	11	5
59	Zotye Holding Group	125,725	0.94	3.59	1	1	1	5
55	Volvo Trucks Group	125,136	0.10	27.88	4	14	22	27
46	Shaanxi Automobile Group	109,993	1.00	1.00	1	1	1	1
39	Paccar	105,418	0.30	20.65	1	5	15	22
51	Tesla	102,470	0.37	17.00	1	2		24
60	Fiat Industrial	94,701	0.13	24.60	3	10	18	
25	Hinduja Group	94,462	0.99	2.71	1	1	2	2
17	GAZ Group	93,462	0.77	5.00	1	1	4	3
60	CNH Industrial	89,150	0.10	31.86	4	9		33
41	Porsche	82,454	0.17	34.67	2	9	24	
65	Fujian Motor Industry Group Co. (FJMG)	81,189	1.00	1.12	1	1	1	1
37	Navistar	80,275	0.65	6.88	1	2	6	6
22	Haima Automobile Group	66,085	0.96	2.58	1	1		1
43	Qingling Motors (Group)	62,484	1.00	1.00	1	1	1	1
56	Xiamen King Long Motor Group	57,982	0.86	4.82	1	1	1	7
23	Hawtai (Huatai) Automobile Group	49,623	0.99	1.40	1	1		2
47	Sollers Group	48,212	0.91	3.00	1	1	2	4
24	Hebei Zhongxing Automobile Mfg.	44,015	0.79	3.35	1	1	1	1
58	Yutong Bus Group	42,781	0.96	4.12	1	1	1	6
63	Eicher Group	36,410	1.00	1.24	1	1	1	2
57	Yulon Group	31,399	0.58	2.00	1	2		2
64	Force Motors	20,713	1.00	1.00	1	1	1	1
26	Hindustan Motors	8,809	1.00	1.00	1	1	1	
10	Daewoo Bus Corporation	2,971	0.69	1.76	1	1	1	4
2	Aston Martin	2,397	0.19	20.77	2	7		25
32	KAMAZ Group	810	0.49	1.14	1	2		2
53	VDL Group	718	0.14	8.82	3	7	7	7

Note: The sales data we're looking at covers the years 2004 to 2020. Here's what the variables mean:

- ”Mean Annual Sales”: This is the average yearly sales across all countries.
- ”Geographic Concentration”: This measures how sales are spread out across countries. It is calculated like an Herfindahl-Hirschman index: $\sum_c s_{ic}^2$ when s_{ic} is the share of sales that carmaker i has in country c. The closer the result is to 1, the more a carmaker's sales are focused in just a few countries.
- ”Mean Number of Countries”: This tells us the average number of countries a carmaker sells in each year.
- ”Mean Number of Countries with 50% (or 80%)”: This shows the number of largest markets (i.e., country-level sales) which together add up to 50% (or 80%) of a carmaker's total sales. The value reflects the mean number of such markets across years.
- ”Number of Countries in 2014 (or 2018)”: This tells us how many countries a carmaker sold in for that specific year, either 2014 or 2018.

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Table A.3
Summary Statistics of Carmakers' Suppliers

	count	mean	sd	min	max
Nbr of suppliers connected to carmaker	500	62.16	85.01	1.00	508.00
Nbr of suppliers (from relevant industries) connected to carmaker	500	44.06	59.00	1.00	361.00
Nbr of links that the average supplier of the carmaker has	500	8.92	3.83	1.00	30.00
Nbr of links that the average supplier of the carmaker has (weighted by age)	500	1.47	2.83	0.03	30.00
Percent of suppliers shared by 10+ carmakers (%)	500	42.01	24.81	0.00	100.00
Age of the link between carmaker and its mean supplier	500	2.76	1.24	1.00	8.00

Note: Relevant industries for suppliers are defined as the following two-digit NAICS code: 31-33 (Manufacturing), 42 (Wholesale trade), 44 (Retail trade) and 54 (Professional, Scientific, and Technical Services).

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B PATENT DATA

B.1 Patent Classification

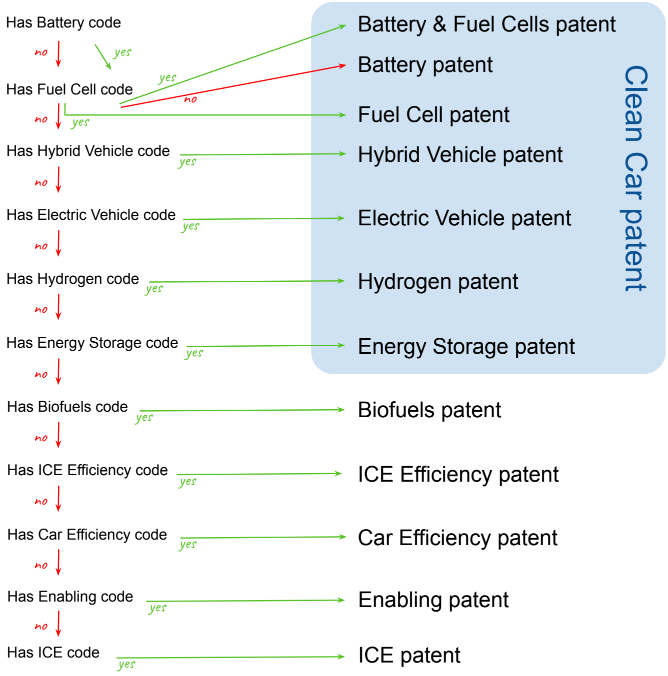

Figure B.1
Classifying Patents into Exclusive Technology Types

Note: This illustrates how we classify patents into exclusive categories. For example, if a patent family presents a battery and hydrogen code, it will be classified in battery only, and not in hydrogen. We do this for most patents. But if a patent mentions both batteries and fuel cells, we put it in a special category called ”Battery & Fuel Cells patent”.

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Table B.1
CPC and IPC Codes for Clean Transportation Technologies

Sub-sector	Code	Description
Batteries	B60L50/60	Using power supplied by batteries
	B60L53	Methods of charging batteries, specially adapted for electric vehicles; Charging stations or on-board charging equipment therefor; Exchange of energy storage elements in electric vehicles
	B60L53/53	Charging stations characterised by energy-storage or power-generation means – batteries
	B60L58/10	Methods or circuit arrangements for monitoring or controlling batteries or fuel cells, specially adapted for electric vehicles – batteries
	B60R16/033	Characterised by the use of electrical cells or batteries
	B60R16/04	Arrangement of batteries
	B60S5/06	Supplying batteries to or removing batteries form
	Y02E60/10	Energy storage using batteries, capacitors, Mechanical energy storage, e.g. flywheels or pressurised fluids
	Y02T10/70	Energy storage for electromobility, e .g. batteries
	Y02T90/10	Technologies relating to charging of electric vehicles
Electric Vehicles	B60K1	Arrangement or mounting of electrical propulsion units
	B60K16	Arrangements in connection with power supply of propulsion units in vehicles from forces of nature, e.g. sun or wind
	B60L	Propulsion of electrically-propelled vehicles
	B60L11	Electric propulsion with power supplied within the vehicle
	B60L11/18	Electric propulsion with power supplied within the vehicle - using power supplied from primary cells secondary cells or fuel cells
	B60L15	Methods circuits or devices for controlling the traction-motor speed of electrically-propelled vehicles
	B60L3	Electric devices on electrically propelled vehicles for safety purposes - monitoring operating variables e.g. speed deceleration power consumption
	B60L50	Electric propulsion with power supplied within the vehicle
	B60L7	Electrodynamic brake systems for vehicles in general
	B60L8	Electric propulsion with power supply from forces of nature, e.g. sun or wind
	B60W10	Conjoint control of vehicles sub-units of different type or different function
	Y02T10/64	Electric machine technologies in electromobility
	Y02T10/72	Electric energy management in electromobility
Enabling Technologies	Y02T90	Technologies relating to charging of electric vehicles
Energy Storage	B60L53/50	Charging stations characterised by energy-storage or power-generation means
	H01M	Conversion of chemical energy into electrical energy
Fuel Cells	B60L50/70	Using power supplied by fuel cells
	B60L53/53	Charging stations characterised by energy-storage or power-generation means – fuel cells
	B60L58/30	Methods or circuit arrangements for monitoring or controlling batteries or fuel cells, specially adapted for electric vehicles – fuel cells
	B60W10/28	Conjoint control of vehicle sub-units of different type or different function; including control of fuel cells
	H01M8/00	Fuel cells; manufacture thereof
	Y02E60/50	Fuel Cells
	Y02T90/40	Application of hydrogen technology to transportation, e.g. using fuel cells
Hybrid Vehicles	B60K6	Arrangement or mounting of plural diverse prime-movers for mutual or common propulsion e.g. hybrid propulsion systems comprising electric motors and internal combustion engines
	B60L7/20	Regenerative braking - Braking by supplying regenerated power to the prime mover of vehicles comprising engine -driven generators
	B60W20	Control systems specially adapted for hybrid vehicles
	Y02T10/62	Hybrid vehicles
Hydrogen	Y02E60/30	Hydrogen Technology
Smart Grids	Y02T90/167	Systems integrating technologies related to power network operation and ICT for supporting the interoperability of electric or hybrid vehicles, i.e. smart grids as interface for battery charging of electric vehicles [EV] or hybrid vehicles [HEV]
	Y02T90/168	Systems integrating technologies related to power network operation and ICT for supporting the interoperability of electric or hybrid vehicles, i.e. smart grids as interface for battery charging of electric vehicles [EV] or hybrid vehicles [HEV]
	Y02T90/169	Systems integrating technologies related to power network operation and ICT for supporting the interoperability of electric or hybrid vehicles, i.e. smart grids as interface for battery charging of electric vehicles [EV] or hybrid vehicles [HEV]

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Table B.2
CPC and IPC Codes for Dirty Transportation Technologies

Sub-sector	Code	Description
Internal Combustion Engine	B60K13	Arrangement in connection with combustion air intake or gas exhaust of propulsion units
	B60K15	Arrangement in connection with fuel supply of combustion engines
	B60K28	Safety devices for propulsion-unit control, specially adapted for, or arranged in, vehicles, e.g. preventing fuel supply or ignition in the event of potentially dangerous conditions
	B60K5	Arrangement or mounting of ICE
	F02B	Internal-combustion piston engines; combustion engines in general
	F02D	Controlling combustion engines
	F02F	Cylinders pistons or casings for combustion engines; arrangement of sealings in combustion engines
	F02M	Supplying combustion engines with combustiles mixtures or constituents thereof
	F02N	Starting of combustion engines
	F02P	Ignition (other than compression ignition) for internal-combustion engines

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Table B.3
CPC and IPC Codes for Grey Transportation Technologies

Sub-sector	Code	Description
Biofuels	B67D7/0498	Apparatus or devices for transferring liquids from bulk storage containers or reservoirs into vehicles or into portable containers; Arrangements specially adapted for transferring biofuels
	F02D19/0652	Controlling engines characterised by pluralities of fuels; Biofuels
	Y02E50	Technologies for the production of fuel of non-fossil origin (Biofuels, e.g. bio-diesel, Fuel from waste, e.g. synthetic alcohol or diesel)
	Y02T10/30	Use of alternative fuels, e.g. biofuels
	Y02T70/5218	Maritime or waterways transport; Less carbon-intensive fuels, e.g. natural gas, biofuels
Biomass and Waste	F02B43/08	Engines or plants operating on gaseous fuel generated from solid fuel, e.g. wood
Car Efficiency	Y02T10/80	Technologies aiming to reduce greenhouse gasses emissions common to all road transportation technologies
ICE Efficiency	F02B1/12	Engines characterised by fuel-air mixture compression ignition
	F02B11	Engines characterised by both fuel-air mixture compression and air compression, or characterised by both positive ignition and compression ignition, e.g. in different cylinders
	F02B13/02	Engines characterised by the introduction of liquid fuel into cylinders by use of auxiliary fluid; Compression ignition engines using air or gas for blowing fuel into compressed air in cylinder
	F02B3/06	Engines characterised by air compression and subsequent fuel addition; with compression ignition
	F02B47/06	Methods of operating engines involving adding non-fuel substances or anti-knock agents to combustion air fuel or fuel-air mixtures of engines the substances including non-airborne oxygen
	F02B49	Methods of operating air – compressing compression - ignition engines involving introduction of small
	F02B7	Engines characterised by the fuel-air charge being ignited by compression ignition of an additional fuel
	F02D41	Electric control of supply of combustion mixture or its constituents
	F02M23	Apparatus for adding secondary air to fuel-air mixture
	F02M25	Engine-pertinent apparatus for adding non-fuel substances or small quantities of secondary fuel to combustion-air main fuel or fuel-air mixture
	F02M3	Idling devices for carburettors preventing flow of idling fuel
	F02M39	Fuel injection apparatus
	F02M41	Fuel injection apparatus
	F02M43	Fuel injection apparatus
	F02M45	Fuel injection apparatus
	F02M47	Fuel injection apparatus
	F02M49	Fuel injection apparatus
	F02M51	Fuel injection apparatus
	F02M53	Fuel injection apparatus
	F02M55	Fuel injection apparatus
	F02M57	Fuel injection apparatus
	F02M59	Fuel injection apparatus
	F02M61	Fuel injection apparatus
	F02M63	Fuel injection apparatus
	F02M65	Fuel injection apparatus
	F02M67	Fuel injection apparatus
	F02M69	Fuel injection apparatus
	F02M71	Fuel injection apparatus
	Y02T10/10	Conventional vehicles (based on internal combustion engine)
Mitigation Air	Y02T50	Aeronautics or air transport
Mitigation Maritime	Y02T70	Maritime or waterways transport
Mitigation Rail	Y02T30	Rail Transport

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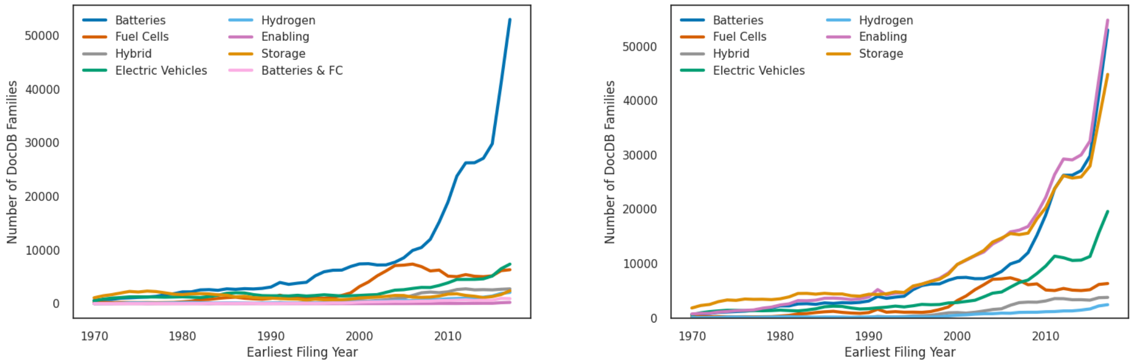
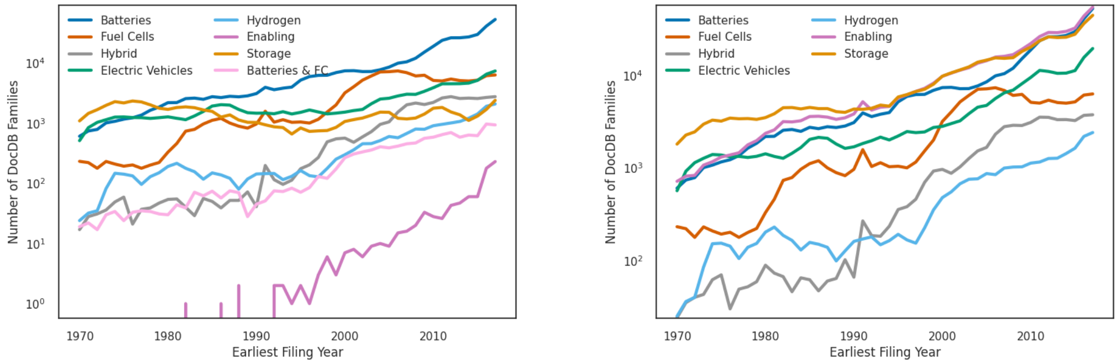
B.2 Patenting Trends at the Family Level



(a) Exclusive Classification (linear scale) (b) Non-Exclusive Classification (linear scale)



(c) Exclusive Classification (log scale) (d) Non-Exclusive Classification (log scale)

Figure B.2
Total Number of Clean Cars Patent Families in PATSTAT

Note: The non-exclusive graphs use non-exclusive counts. That is, if a family has both a code for battery and a code for hybrid, it is counted in both “Batteries” and “Hybrid”.

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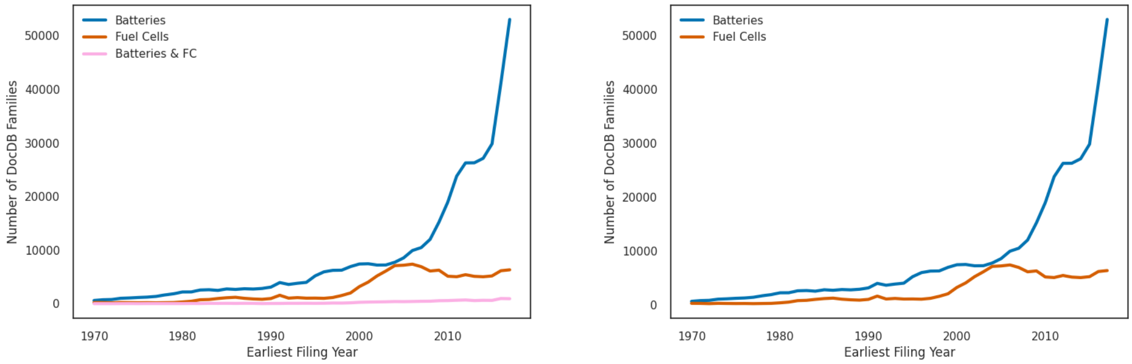
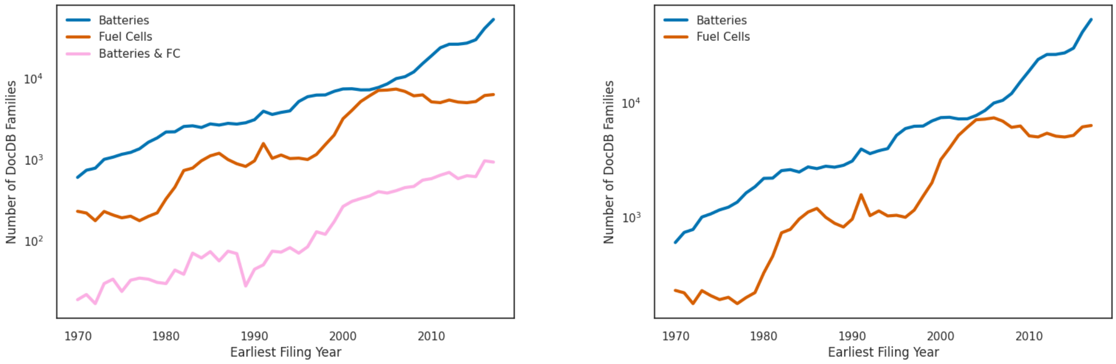


(a) Exclusive Classification (linear scale)

(b) Non-Exclusive Classification (linear scale)



(c) Exclusive Classification (log scale)

(d) Non-Exclusive Classification (log scale)

Figure B.3
Total Number of Battery and Fuel Cells Patent Families in PATSTAT

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C PATENTING TRENDS

C.1 Patenting Trends for Carmakers

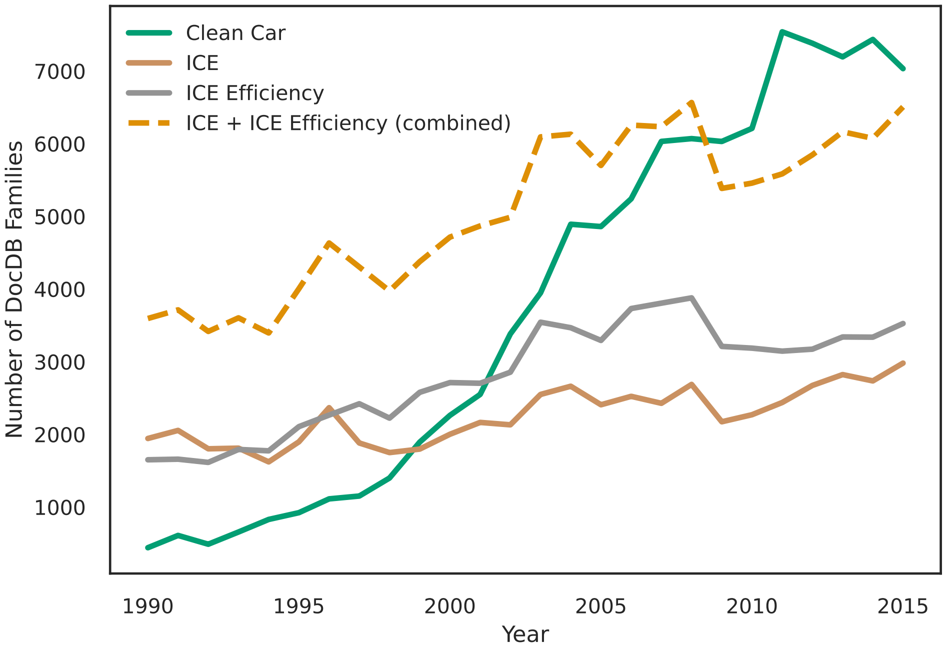
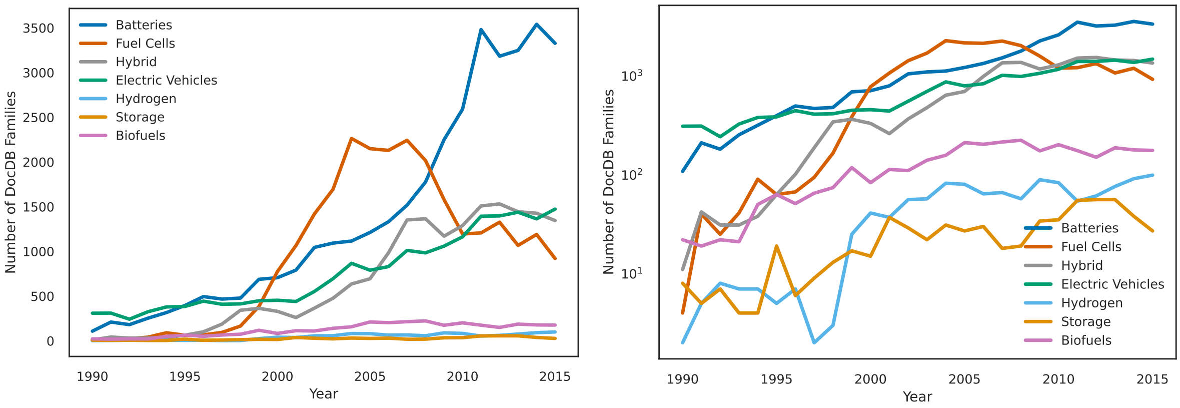


Figure C.1
Carmaker patenting on the ICE versus clean cars



(a) Linear scale

(b) Log scale

Figure C.2
Counts of Carmakers' patents by type of technology (log scale)

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C.2 Additional Graphs for Sectoral Decomposition

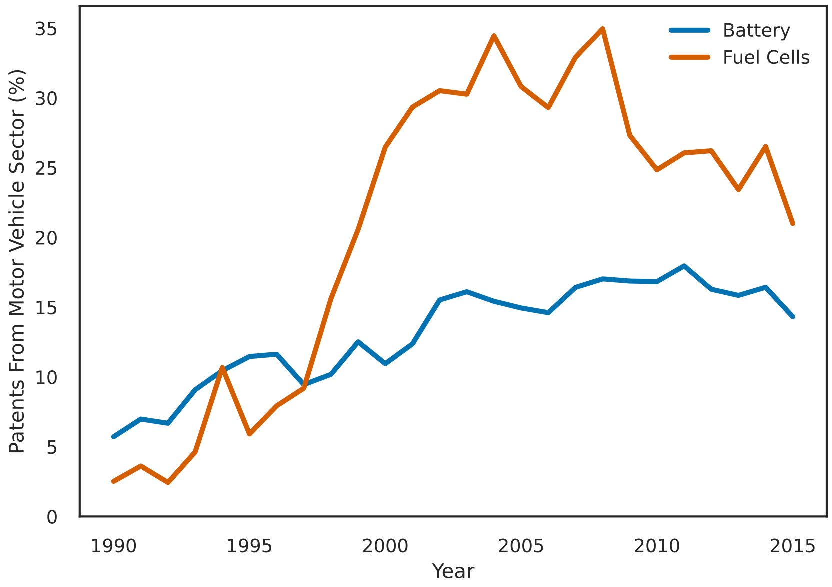

Figure C.3
Battery and Fuel Cell Patenting: Percentage of Motor Vehicles in Total

C.3 Measuring Spillovers with Citations

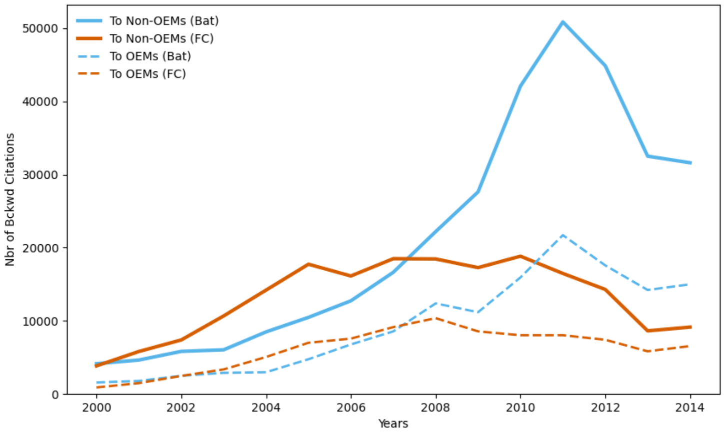

Figure C.4
Backward Citations made by Carmakers to other industries outside Motor Vehicles.

Note: The figure shows that car makers have been drawing more on the pool of knowledge outside of their industry than within. This highlights the importance of innovation trends in other sectors.

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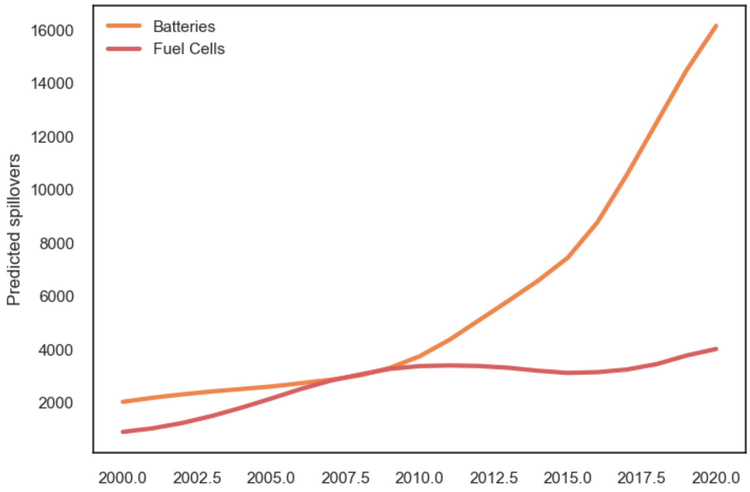

Figure C.5
Expected battery and fuel cell spillovers to OEMs from outside the industry.

Note: As explained in the main manuscript (see Methods), we compute a measure of expected spillovers which, unlike the basic counts of citations, control for contemporaneous changes in carmakers' patenting activity. The figure here plots the expected spillovers arising from innovation by non-OEM firms, for battery and fuel cells respectively, over time. Unlike the basic counts of citations, these expected spillovers control for contemporaneous changes in OEM's patenting activity. The figure shows that spillovers for batteries largely came to dominate those from fuel cells after 2010 due to the larger amount of available knowledge from outside the industry. This shows that the automotive industry was able to ride the wave of battery innovations happening most prominently in Electronics. For fuel cells, although OEMs were able to absorb knowledge from the outside in their work on fuel cells, there was no complementary innovation wave in other sectors to sustain cross-sectoral learning.

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C.4 Additional Information about New Suppliers

Table C.1
Top 10 New Suppliers

Name	Region	New Supplier Battery Count	Battery Stock	Overall Stock	Nbr OEMs	% New Links
lg chem co ltd	KR	37.04%	2188	6054	8	0.44%
samsung sdi co ltd	KR	15.13%	2241	6157	7	0.39%
panasonic corporation	JP	14.26%	2046	49160	7	0.39%
toshiba corporation	JP	6.43%	641	36850	3	0.17%
hitachi ltd	JP	3.21%	541	18572	5	0.28%
yazaki corporation	JP	2.98%	309	5134	4	0.22%
mitsubishi electric corporation	JP	2.46%	326	27019	4	0.22%
nec corporation	JP	2.42%	369	16278	1	0.06%
sk innovation co ltd	KR	1.92%	348	829	3	0.17%
sharp corporation	JP	1.59%	294	24142	1	0.06%

Table C.2
Top 10 New Suppliers from the US

Name	Region	New Supplier Battery Count	Battery Stock	Overall Stock	Nbr OEMs	% New Links
boeing company the	US	0.40%	40	3643	2	0.11%
corning inc	US	0.20%	47	1647	3	0.17%
maxwell technologies inc	US	0.12%	16	26	7	0.39%
deere co	US	0.09%	20	1292	1	0.06%
raytheon company	US	0.08%	6	1466	2	0.11%
microsoft corporation	US	0.07%	10	12289	5	0.28%
exide technologies	US	0.07%	5	15	4	0.22%
parker hannifin corp	US	0.02%	3	339	7	0.39%
texas instruments inc	US	0.02%	7	3017	2	0.11%
basf corp	US	0.02%	32	283	1	0.06%

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D POLICY DATA AND ANALYSIS

D.1 Data Collection

Table D.1 shows how we have coded the strategic orientation of different countries over time. To infer strategic orientation, we read the text of flagship policies where possible, or accounts by other authors that provide detail of flagship policies (references are provided in the Table). Flagship policies are any laws, plans or programmes that provide an overall orientation for the automotive sector and take precedence over the programmes of agencies with narrower remit. If a policy or law has the explicit aim of furthering a particular clean vehicle technology, then we code this as the technological focus of the policy. If multiple policies co-exist with different technological foci, or if policies are explicitly technology neutral, then we infer that there is no single technological focus. If there is no overarching plan, then we code this accordingly.

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Table D.1
Technological Focus of Different Countries

Country	Period	Primary technology	Secondary technology	Strategy name	References
Japan	1976-1986	BEVs		Electric Vehicles Market Expansion Plan	Åhman (2006)
	1991-1997	BEVs		Electric Vehicles Market Expansion Plan	Åhman (2006); Pohl and Yarime (2012)
	1997-2001	All types		Electric Vehicles Market Expansion Plan	Åhman (2006); Pohl and Yarime (2012)
	2001-2010	FCEVs		Policy Study Group on Fuel Cell Commercialization (2001); Fuel Cell Conference of Japan (FCCJ): inter-industry and government coordination body; Roadmap for PEFCs, targeting penetration by 2010	Maeda (2003);Ishitani and Baba (2008)
	2010-2020	PHEVs, BEVs	FCEVs	Next Generation Automotive Strategy; EV and PHV roadmap	METI (2011);METI (2018)
China	1995-2000	All types		9th YP	Gong, M. Q. Wang, and H. Wang (2013);ICCT (2021)
	2000-2010	Equal focus on FCEVs, BEVs and HEVs		Numerous plans: 10th YP; 11th YP; Development Policy of Auto Industry; Energy Saving Medium and Long-term Plan; Electric Vehicle Special Project under the Tenth YP (2001-2005); National High-Tech R&D Program (863 Program)	Gong, M. Q. Wang, and H. Wang (2013);ICCT (2021)
	2010-2020	BEVs	FCEVs	12th YP; Auto Industry Adjustment and Revitalization Plan; Decisions on Accelerating the Cultivation and Development of Emerging Strategic Industries in October 2010; Options on Accelerating the Development of Energy Savings and Environmental Protection Industry; Energy-Saving and New Energy Vehicle Development Plan (2012-2020); Medium and Long-Term Development Plan for the Automotive Industry (2017)	Gong, M. Q. Wang, and H. Wang (2013);ICCT (2021)
Korea	2003-2010	FCEVs		10-Year National Plan for Energy Technology Development; National Vision for Hydrogen	Leflaive (2008);M.-K. Kim, J.-H. Park, K. Kim, et al. (2020)
	2010-2016	BEVs		Green Car Promotion Strategy; Green Car Industry Stimulation Plan	Hwang (2015)
	2016-	BEVs	FCEVs	June 3 Measures; Net-Zero pledge; Hydrogen Economy Roadmap (2020)	
France	1992-1999	BEVs		Accord-cadre sur le developpement du vehicule electrique	Calef and Goble (2007)
	1999-2008	No clear strategy		French inter-ministry committee for clean vehicles	CIVP (2000)
	2009-2020	BEVs, PHEVs		Plan national pour le développement des véhicules électriques et hybrides rechargeables (Plan Véhicules Décarbonés); Pacte Automobile	
UK	2002-2017	All types (technology neutral)		Power Future Vehicles Strategy; ULEV strategy; Driving the Future Today	DfT UK (2002);OLEV (2013)
	2017-2020	BEVs, PHEVs	FCEV	Road to Zero strategy; Automated and Electric Vehicles Bill	DfT UK (2018)
Germany	-2008	No clear strategy		German Federal Government's 3rd Transport Research Programme on Mobility and Transport Technologies; National Innovation Programme Hydrogen and Fuel Cell Technology	BMWi (2008);BMDV (2016)
	2008	BEV		German Federal Government's Economic Stimulus Package II	
	2009-2020	BEV	FCEV	National Electromobility Development Plan; Nationale Plattform Elektromobilität	Bundesregierung (2009)
USA	1988-2001	Biofuels		Alternative Motor Fuels Act	Liu and Helfand (2009)
	2001-2009	FCEVs	BEV (as plan B)	President's National Energy Policy; Energy Policy Act of 2005; Hydrogen Posture Plan	DOE (2002);DOE (2006);NRC (2005)
	2008-2016	PHEVs, BEVs	FCEV for heavy-duty	American Recovery and Reinvestment Act; The EV Everywhere Grand Challenge Blueprint	DOE (2013);Canis (2013)
	2016-2020	no clear strategy		No large-scale policy targeting a particular technology or nation-wide target. State-level market-pull initiatives.	

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Table D.2
RD&D Funding Data Sources for Years

Country	Period	Technology	Source
France	1995-2001	Hydrogen fuel cells	OECD (2006)
	2001-2020	Both technologies	IEA database
Korea	1995-2002	Hydrogen fuel cells	OECD (2006)
	2004-2020	Both technologies	IEA database
Japan	1995-2001	Hydrogen fuel cells	Maeda (2003)
	2002-2006	Hydrogen fuel cells	Ishitani and Baba (2008)
	1992-2002	Other energy storage	Åhman (2006)
	2004-2020	Both technologies	IEA database
USA/DOE	1995-2003	Both technologies	Kelly S Gallagher and Anadon (2021)
	2004-2015	Both technologies	IEA database
	2016-2020	Both technologies	Kelly S Gallagher and Anadon (2021)
China	1995-2000	Both technologies	Zhang, Kelly Sims Gallagher, Myslikova, et al. (2021)

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D.2 Firm-Level Regressions

Table D.3
Exposure to National Orientations and Battery/FC Focus

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
FC Orientation t-1	-0.03	-0.11	-0.19	-0.23					0.10	0.04	-0.04	-0.10
	(0.09)	(0.08)	(0.17)	(0.15)					(0.11)	(0.10)	(0.23)	(0.18)
FC Orientation	0.05	0.04	0.17	0.11					0.11	0.09	0.20	0.11
	(0.08)	(0.07)	(0.17)	(0.16)					(0.11)	(0.10)	(0.21)	(0.21)
FC Orientation t+1	-0.27^{***}	-0.30^{***}	0.11	0.09					0.04	-0.02	0.11	0.07
	(0.08)	(0.09)	(0.16)	(0.14)					(0.13)	(0.12)	(0.19)	(0.16)
BEV Orientation t-1					0.25^{***}	0.21^{***}	0.37^{**}	0.26^{*}	0.28^{***}	0.22^{***}	0.37^{*}	0.23
					(0.06)	(0.06)	(0.15)	(0.14)	(0.08)	(0.07)	(0.19)	(0.16)
BEV Orientation					-0.01	0.00	-0.05	-0.06	0.06	0.06	0.08	0.00
					(0.07)	(0.07)	(0.10)	(0.09)	(0.10)	(0.09)	(0.11)	(0.12)
BEV Orientation t+1					0.13^{*}	0.10	-0.01	-0.10	0.13	0.08	0.10	-0.04
					(0.07)	(0.07)	(0.20)	(0.19)	(0.10)	(0.10)	(0.25)	(0.23)
Year FEs			X	X			X	X			X	X
Firm FEs		X		X		X		X		X		X
Firm Clusters (SEs)	44	41	44	41	44	41	44	41	44	41	44	41
R2	0.04	0.49	0.18	0.56	0.18	0.54	0.20	0.56	0.20	0.54	0.21	0.56
Observations	456	453	456	453	456	453	456	453	456	453	456	453

Dependent variable: Difference between Share of Battery and FC.
OLS. Cluster-robust standard errors in parentheses. * p<0.10, ** p<0.05, *** p<0.01

Table D.4
Exposure to RD&D Funding and Battery/FC Focus

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
FC R&D t-1	0.78	0.82^{*}	-0.14	0.01					0.45	0.74^{*}	-0.25	0.18
	(0.51)	(0.46)	(0.58)	(0.66)					(0.48)	(0.41)	(0.59)	(0.64)
FC R&D	-0.08	-0.43	-0.09	-0.66					-0.27	-0.50	-0.21	-0.61
	(0.72)	(0.65)	(0.73)	(0.72)					(0.70)	(0.68)	(0.74)	(0.75)
FC R&D t+1	-2.24^{***}	-2.09^{***}	-0.85	-1.14					-1.44^{**}	-1.76^{***}	-0.58	-1.47
	(0.58)	(0.56)	(0.73)	(0.77)					(0.68)	(0.64)	(0.86)	(0.95)
BEV R&D t-1					0.33^{***}	0.39^{***}	-0.01	0.08	0.10	0.06	-0.04	-0.17
					(0.08)	(0.10)	(0.10)	(0.12)	(0.10)	(0.10)	(0.13)	(0.15)
BEV R&D					0.20^{***}	0.18^{**}	0.21	0.06	0.15^{**}	0.10	0.22^{*}	0.07
					(0.06)	(0.08)	(0.13)	(0.15)	(0.06)	(0.08)	(0.13)	(0.15)
BEV R&D t+1					0.17^{*}	0.08	0.05	-0.25	0.16^{*}	0.05	0.04	-0.14
					(0.10)	(0.09)	(0.15)	(0.16)	(0.09)	(0.09)	(0.14)	(0.15)
Year FEs			X	X			X	X			X	X
Firm FEs		X		X		X		X		X		X
Firm Clusters (SEs)	44	41	44	41	44	41	44	41	44	41	44	41
R2	0.13	0.50	0.20	0.56	0.10	0.47	0.19	0.55	0.15	0.51	0.21	0.56
Observations	456	453	456	453	456	453	456	453	456	453	456	453

Dependent variable: Difference between Share of Battery and FC.
OLS. Cluster-robust standard errors in parentheses. * p<0.10, ** p<0.05, *** p<0.01

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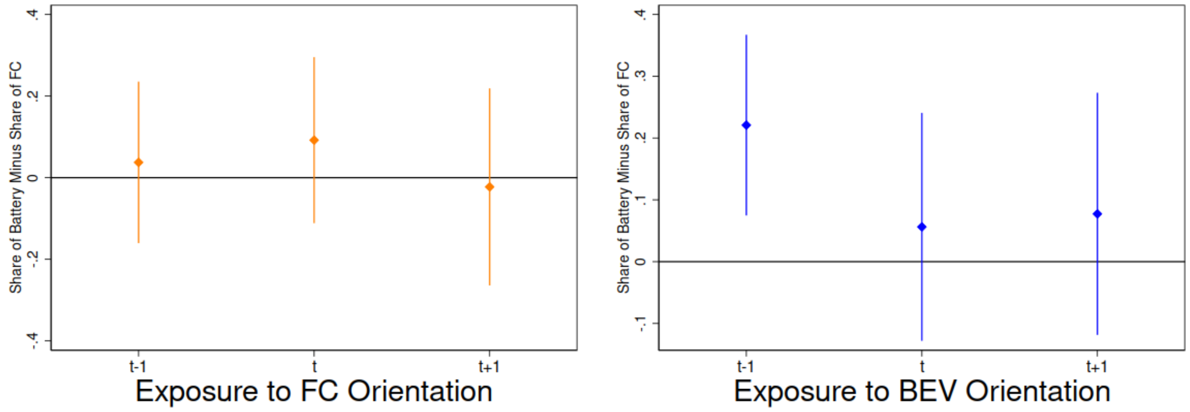
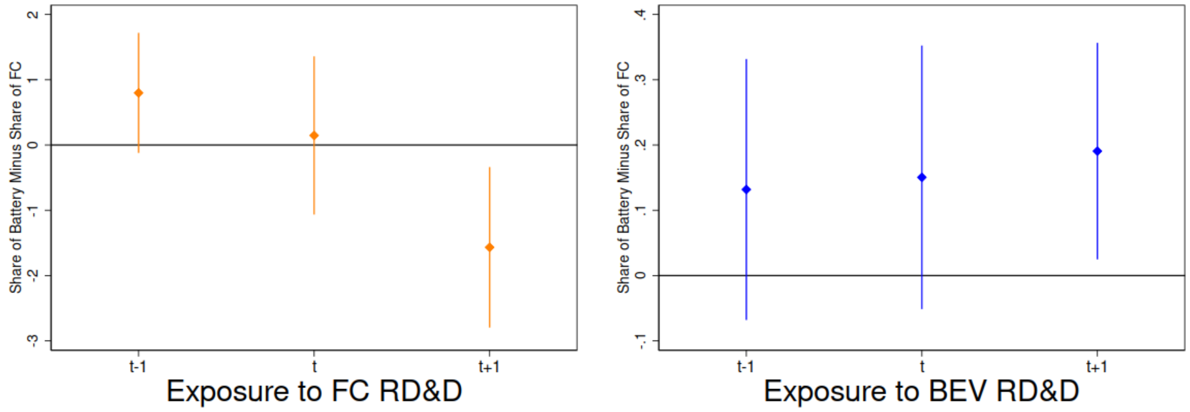


(a) Coefficients for Column 10 in Table D.3



(b) Coefficients for Column 10 in Table D.4

Figure D.1
Fuel Cells vs. BEV Policies

Note: Figure D.1a plots the coefficients from regression (10) in Table D.3, while Figure D.1b plots the coefficients from regression (10) in Table D.4.

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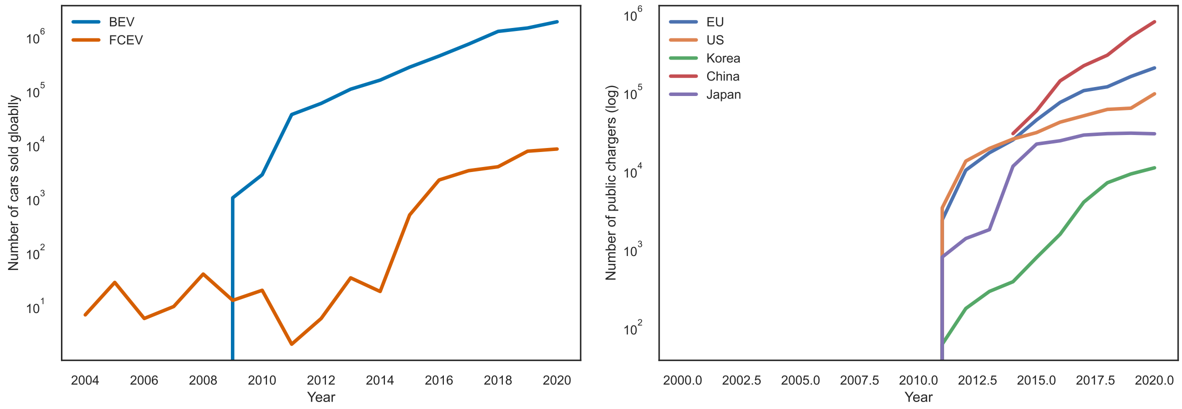
E OTHER ADDITIONAL INFORMATION

Table E.1
Data Sources for Fuel Cell Prices

Year	Source
1996	Barbir, F., and T. Gómez. 1997. "Efficiency and Economics of Proton Exchange Membrane (PEM) Fuel Cells." International Journal of Hydrogen Energy 22 (10): 1027–37.
2000	US Department of Energy. 2000. "Cost Analysis of Fuel Cell." https://afdc.energy.gov/files/pdfs/baseline_cost_model.pdf.
2002	US Department of Energy. 2010. "Overview of Hydrogen and Fuel Cell Activities." https://www.hydrogen.energy.gov/pdfs/htac_oct1410_overview.pdf.
2006-2017	US Department of Energy. 2017. "Fuel Cell Technologies Office Record 17007: Fuel Cell System Cost." https://www.hydrogen.energy.gov/pdfs/17007_fuel_cell_system_cost_2017.pdf.



(a) Sales of BEVs and FCEVs (log scale)

(b) Number of public chargers (log scale)

Figure E.1
EV sales and charger availability start in earnest after 2010

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