Coordination dynamics between fuel cell and battery technologies in the transition to clean cars *

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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 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 fuel cell electric vehicles (FCEVs) and battery electric vehicles (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, coinciding with a wave of exogenous battery advancements in electronics. Our findings underscore the role of cross-sectoral spillovers and provide a rationale for globally coordinated industrial policies.

Keywords: Energy innovation, Electric cars, Fuel cells, Coordination, Low-Carbon Transitions.

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

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two technologies. While the industry initially focused on FCEVs, around 2008, the technological paradigm shifted to BEVs. 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 BEVs. 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.

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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 are not 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?[1]

Understanding why the industry favored BEVs over FCEVs 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 externalities 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 and only one dominant technology can emerge in the globally integrated market and production network for lightweight vehicles. Importantly, there was no clear superiority between BEVs and FCEVs. Both presented significant pros and cons when considering the transition away from ICE cars.[2]

As described in the Methods section, we then use patent and supply-chain data to track innovation targeted at fuel cells 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 fuel cells before shifting their focus to batteries. No global institutions ever arose to coordinate actors. Instead, a fortuitous wave of

[1] Although BEVs' overall sales are still small compared to ICE vehicles, they significantly exceed those of FCEVs.

[2] For a detailed comparison of their relative advantages and disadvantages, see SI Section E.1.

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 fuel cells and batteries. We also compile a 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. 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 quantitatively studies 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 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 examples, 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].

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 SI2) 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, whether they communicate about it or not. 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.

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.

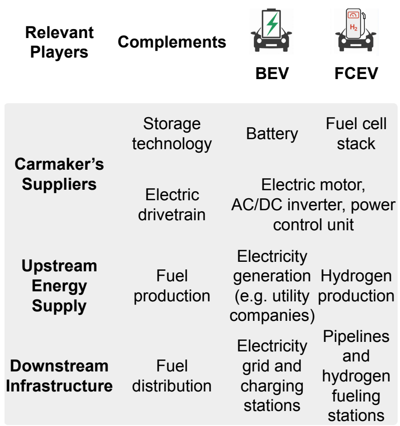
Our framework poses a puzzle: in the absence of an international institutional process to coordinate technological choice, how did the car industry converge on BEVs? This paper looks at two possible answers: 1) national policies and 2) cross-sectoral spillovers that exogenously provided some of the technological 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 (for more details see SI Subsection E.2).[3]

[3]The challenges in upgrading electricity grids for fast-charging stations do not necessarily look easier than

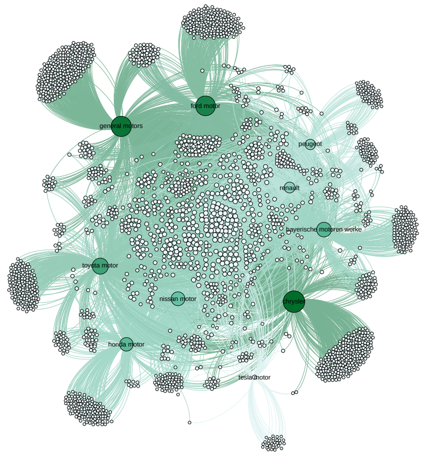
Tesla and Hybrid Cars Viewing the shift to clean cars as a global coordination game also helps explain two notable success stories: the development of hybrid vehicles like the Prius and Tesla's pioneering role in the Electric Vehicles (EVs) market. Hybrid vehicles offered a strategy to radically reduce 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].[4] 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). Crucially, this move sent a strong, observable signal that Li-ion batteries were viable for automotive applications, likely helping the car industry to converge and reach a consensus on the potential of BEVs.

those of developing a hydrogen infrastructure. This is partly because hydrogen can be transported by trucks, allowing for relatively straightforward scalability. The primary bottleneck for FCEVs remains the cost of hydrogen itself. At low-scale adoption, BEVs sidestep issues related to charging infrastructure, battery capacity, and charging times, by appealing to consumers who can charge at home overnight and often buy a BEV as a secondary option to their ICE car. For more details, see SI Section E.1.

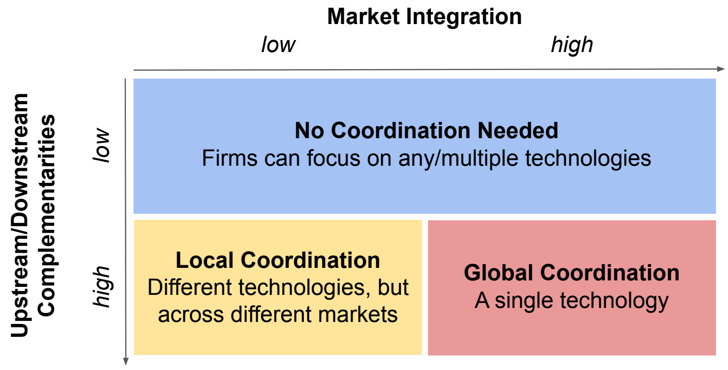
[4]The impact of hybrid technology on BEV adoption is ambiguous, given the different battery types used and the fact that improvements in regenerative braking and electric motors could benefit both BEVs and FCEVs.



(a) Complementarities in Technological Components



(b) A Tightly Integrated Network of Producers and Suppliers



(c) Industry Characteristics and Need for Coordination.

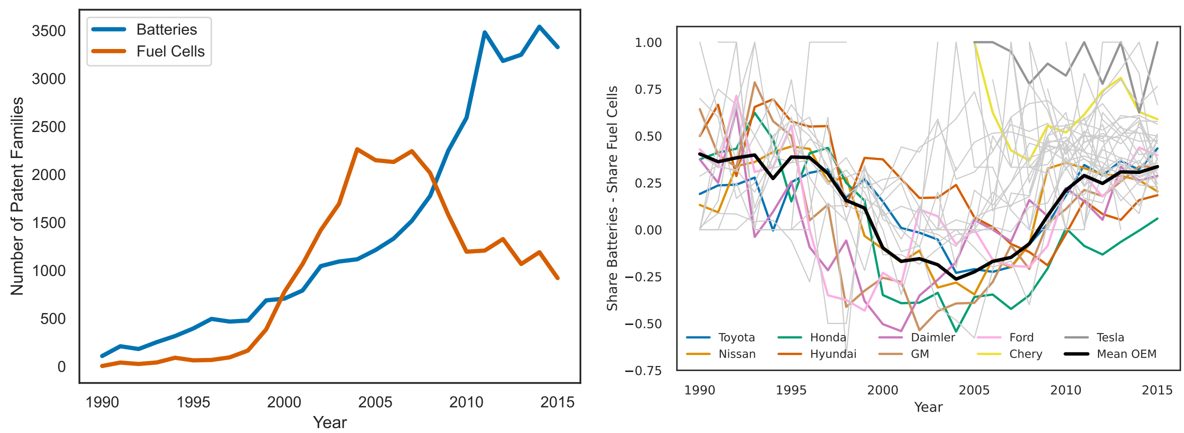
Figure 1
Clean Car Development as a Global Coordination Game. Figure 1a illustrates that road transport systems based on FCEVs and BEVs require very different sets of complements. Figure 1b shows the global tier-1 supplier network for the ten largest carmakers. Green nodes are carmakers; white nodes 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.

Fuel cell 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 2008 (Figure SI8). Yet, a deeper look reveals contrasting trends between fuel cell and battery patenting (Figure 2a).

In the late 1990s, carmakers favored fuel cells, leading to a swift rise in fuel cell patents until 2004. However, by 2007, fuel cells experienced a stark "reversal fortune": fuel cell patenting stagnated and sharply declined. Concurrently, battery patenting accelerated. These shifts align with US media's reported 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 fuel cells and biofuels and reverting to BEVs by 2007 [12]. This reversal of fortune occurred alongside sustained growth in electric vehicle (EV) patents (Figure SI9), 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 fuel cells to batteries is globally synchronized: nearly all major carmakers transitioned similarly, first focusing on fuel cell and later on batteries (Figure 2b). While some initiated this change earlier,[5] 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. Panel 2a plots the number of patent families, filed by at least one carmaker, related to battery or fuel cell technology over time. Panel 2b plots, for each carmaker, the difference between battery and fuel cell 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.

From a fragmented fuel cell policy landscape to a global policy consensus on battery.

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 fuel cells from the late 1990s until 2008 (Figure 3b). It then declined, settling at roughly half of its peak value. Conversely, funding for electric storage remained flat until 2008, after which it surged in most countries, notably China and the USA.[6]

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

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

We then compile and code data on policymakers' *strategic orientation*, frequently outlined in official documents like roadmaps or strategic plans (See SI Section D.1). 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 varied across countries, offering no consistent global direction until 2010 (Figure 3a). Although it is possible that some companies and policy-makers attempted to explicitly coordinate on FCEVs during this period (e.g. the California Fuel Cell Partnership was a prominent forum bringing together major automakers and energy providers to promote FCEVs), national policies remained uncoordinated until 2010. At that point, a global consensus around BEVs emerged, often viewed as a medium-term solution, with some countries contemplating a future shift to FCEVs.[7] Most countries analysed make this shift in 2009 or 2010. For example, the USA shifted focus from FCEVs under the Bush administration to BEVs under the Obama administration. This change was part of a strategy to stimulate the industry following the 2008 financial crisis, offering support to carmakers in return for their commitment to clean vehicle goals.[8] 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 fuel cell patents in carmakers' clean portfolios. This analysis offers a clearer view of the timing of policy changes relative to firms' evolving focus on battery and fuel cell.

For fuel cells, we observe that, in the 2000s, carmakers' fuel cell patenting appears to increase at the same time as exposure to fuel cell orientations increases.[9] 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 fuel cell (at time $t+1$), and, to a degree, to fuel cell orientation, significantly correlates with a decreased focus on battery relative to fuel cell at time t. This indicates that carmakers started ramping up efforts on fuel cells before R&D support materialized. A tentative interpretation is that R&D funding was not the essential element that directed the greater focus on fuel cell. However, we acknowledge that carmakers could have been anticipating policy support.

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 with the industry's shift to BEVs, and we

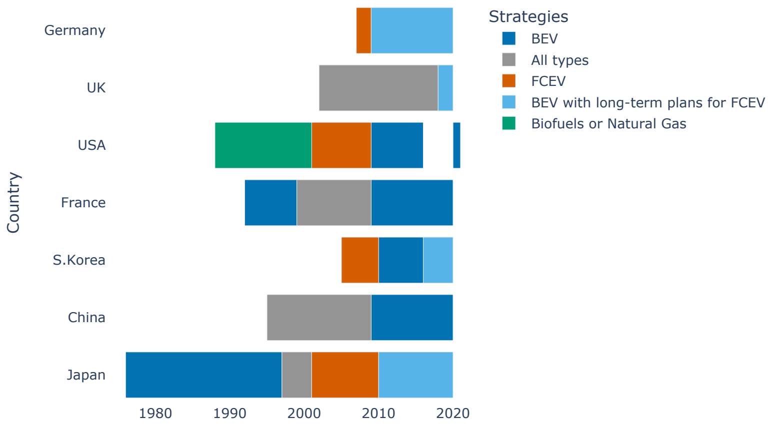
[7] The preference for BEVs now and FCEVs later possibly reflects strategic trade-offs between immediate emission reductions and future technological viability. See SI Section E.1 for more details.

[8] The willingness to impose environmental conditions on carmakers in return for bailout support in 2009 likely further tilted preferences towards BEVs as the immediately more viable clean technology option.

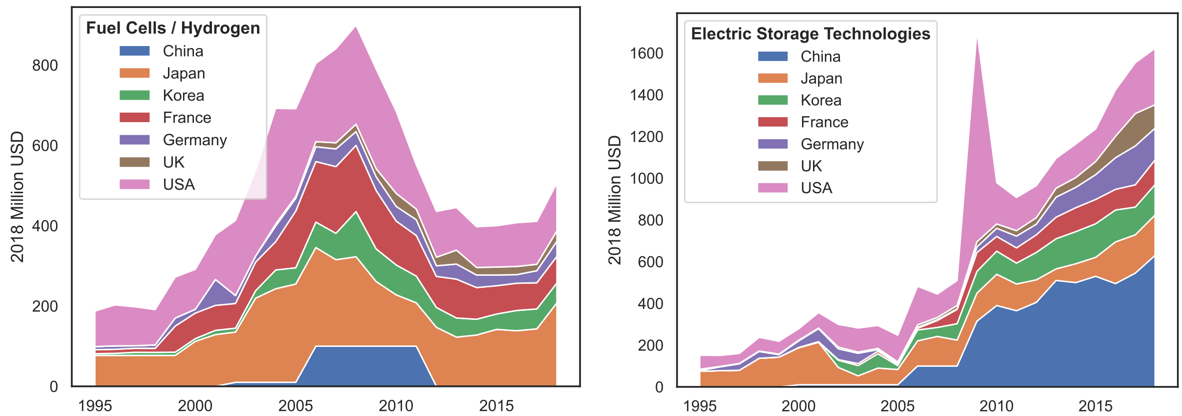
[9] Fuel cell orientation surged in the 2000s, due to policies in the US, Japan, and Korea.

observe that firms with greater exposure to these policy changes were also those with faster increases in battery patenting.[10]

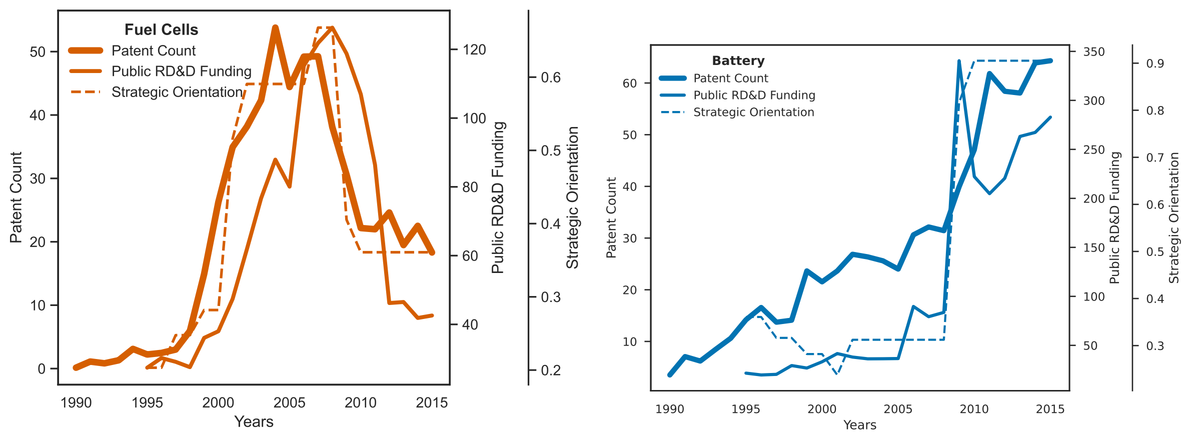
[10]It is possible that the policy shifts induced more battery innovation, however our approach can not say much about this given the possibility for omitted variable bias.



(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. Figure 3a and 3b display the history of strategic orientations and public RD&D funding related to clean vehicles by country over time. The gaps in Figure 3a represent periods without explicit policies on alternative vehicle technology. For instance, during the Trump administration years in the USA, we did not identify any such policies. 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.

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 SI13).

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 fuel cells differs considerably. Here, the Motor Vehicle industry takes center stage, accounting for nearly 35% of all fuel cell 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 fuel cells and hydrogen exhibit significant potential, such as maritime and air transport and machinery. The implication is that the knowledge spillovers from other sectors flowing to carmakers were larger for batteries than fuel cells, as shown in Figure SI14, which plots a measure of *expected* spillovers following [9].[11]

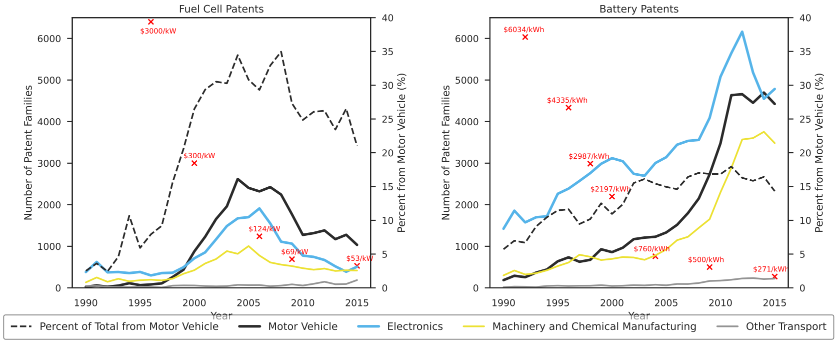
Finally, we examine innovation trends among carmakers' "active" suppliers—those with a recorded supply link to any carmaker in year t. Suppliers are pivotal, not just as input providers, but as conduits for cross-sectoral technological spillovers that can eventually benefit a particular technological 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' fuel cell patent stocks remained low. Moreover, during the height of fuel cell innovation, we do not observe new relationships with fuel cell-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.[12] 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

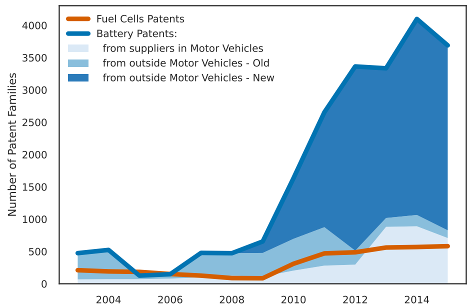
[11] Unlike the raw citation counts of Figure SI13, this measure removes the influence of carmakers' change in patenting and isolate the role of the *availability* of relevant non-carmaker patents. See SI Section C.3 for details.

[12] In SI Section C.4, we document that suppliers don't increase patenting on transport-related battery technologies after partnering with carmakers. Rather, our findings suggest a gradual rise in their overall battery patenting activities, covering both transport and non-transport applications, before their association with carmakers.

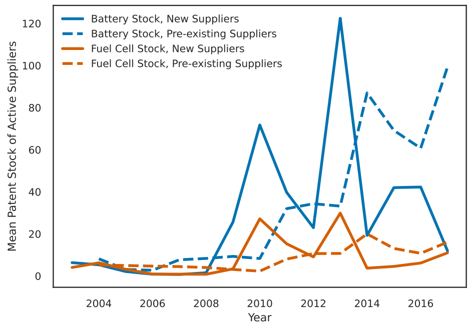
not align with fuel cells.



(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. The figures illustrate the role and importance of cross-sectoral spillovers for innovation on fuel cells and battery technologies. Figure 4a overlays patenting trends outside the car industry and information on the evolution of fuel cells 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 fuel cell 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 fuel cells, 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, car sales and investment in public infrastructure do not start until after the technological uncertainty is resolved (See Figure SI23). This suggests that without policy coordination, a protracted period of technological uncertainty can slow down the transition.

Despite the lack of policy 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. Tesla's emergence likely expedited the consensus-building process among carmakers. Conversely, the failure of fuel cells 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,[13] 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 suggest that global coordination on sector-specific technological choices may hasten the shift to clean technologies in some sectors, 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].

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 SI Section A for details.

[13] For more discussion of the advantages and drawbacks of FCEVs vs BEVs, see SI Section E.1.

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 Table SI3 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 SI 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.[14] 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]. For more details on our measure of expected spillovers, see SI Section 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,

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

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 SI 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.[15].

We then employ a series of regression analyses to delve deeper into the policy-patenting relationship. Results are shown in SI Subsection D.3.

Data and Code Availability

Aggregate data and code have been deposited at the Harvard Dataverse (`https://doi.org/10.7910/DVN/YOEXTM`). Certain data in this study come from custom datasets purchased from Marklines (`www.marklines.com`), Factset Revere (`www.factset.com/marketplace/catalog/product/factset-supply-chain-relationships`), PATSTAT (`www.epo.org/en/searching-for-patents/business/patstat`), and Orbis IP (`login.bvdinfo.com/R0/OrbisIntellectualProperty`). 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 via a replication package we will post on the Harvard Dataverse. Data on public RD&D support is freely available via the International Energy Agency [54]. The additional RD&D observations we collected, the country-year data on

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

strategic orientation, and all code involved in data processing, analysis, and figure generation will also be available via the replication package.

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Competing Interest Declaration

The authors declare no competing interests.

Supporting Online Information

Supplementary Information is attached at the end of this document.

FOR ONLINE PUBLICATION

Online Supplementary Material – Global Coordination Challenges in the Transition to Clean Technology: Lessons from Automotive Innovation

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A Sample of Car Manufacturers and Suppliers

Table SI1
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	Cnh Industrial N.V.
	Fiat Industrial	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

Table SI2
Carmakers Summary Statistics for Country Sales

Carmaker ID	Name	Mean Annual Sales	Geographic Concentration	Mean Number of Countries	Mean Nbr Countries with 50%	with 80%	Nbr Countries in 2004	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.

Table SI3
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: This table presents summary statistics for our dataset at the carmaker-year level. Each variable in the first column is calculated for each carmaker in each year. "Count" indicates the number of carmaker-year observations in our sample, which totals 500. "Mean" represents the average value for each variable across the sample. For instance, the average number of suppliers connected to a carmaker in a given year is 62.16. The standard deviation (sd) measures the variability or dispersion around the mean value of each variable. The minimum (min) and maximum (max) columns show the lowest and highest values recorded for each variable across the sample. For example, the smallest number of suppliers connected to any carmaker in any year was 1, while the largest was 508. Regarding the "Percent of suppliers shared by 10+ carmakers (%)", the maximum value of 100% indicates that in at least one year, a carmaker was connected exclusively to suppliers that were also shared by 10 or more other carmakers. Note that the Factset dataset reports relationships between suppliers and customers among a substantial number of public and private firms worldwide, covering the period from 2003 to 2017. It is possible that the dataset does not capture the complete universe of supplier-customer relationships. However, the database is updated annually and the updates are based on the information gathered by analysts from a range of sources, particularly including SEC filings, press releases, and investor 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).

B Patent Data

B.1 Patent Classification

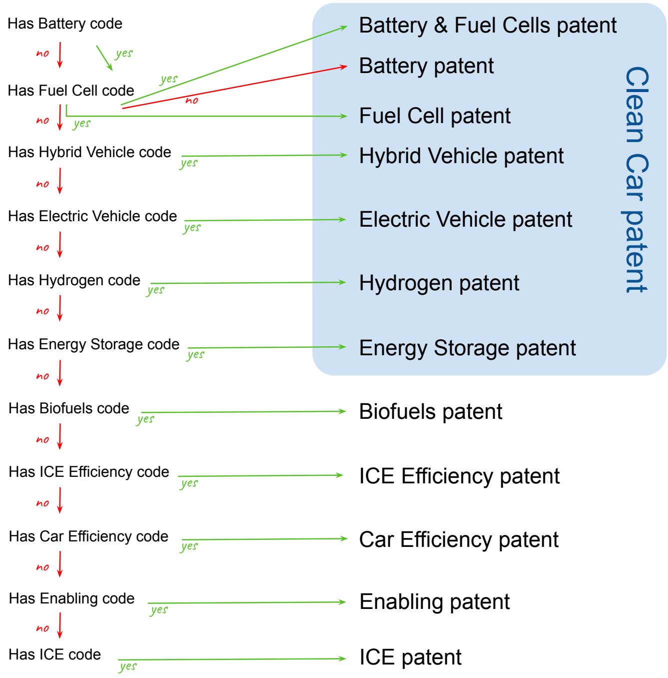


Figure SI1
Classifying Patents into Exclusive Technology Types

Note: This figure illustrates how we classify patents into exclusive categories. For example, a patent family with both battery and fuel cell codes is classified as ”Battery & Fuel Cell”. In contrast, those with a battery code but no fuel cell code are classified as ”Battery only”, irrespective of other codes like hydrogen or ICE. The patent classification system has distinct codes for fuel cells and hydrogen, enabling us to categorize them separately (refer to Table SI4 for more details). This distinction is useful to differentiate inventions specifically related to fuel cells from those pertaining to broader aspects of the hydrogen value chain, including hydrogen storage, distribution, and production.

Table SI4
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]

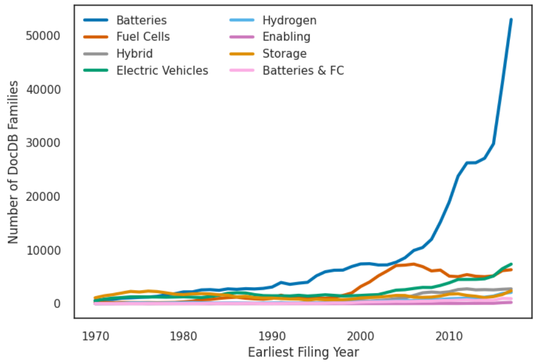
Table SI5
CPC and IPC Codes for Dirty Transportation Technologies

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

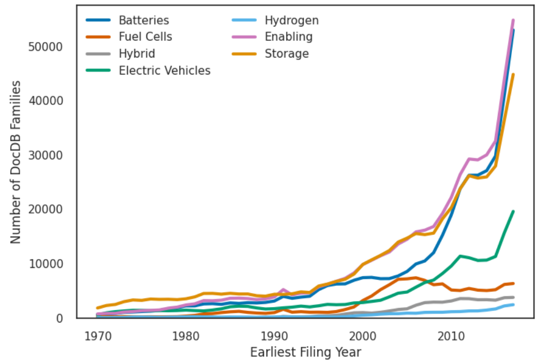
Table SI6
CPC and IPC Codes for Grey Transportation Technologies

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

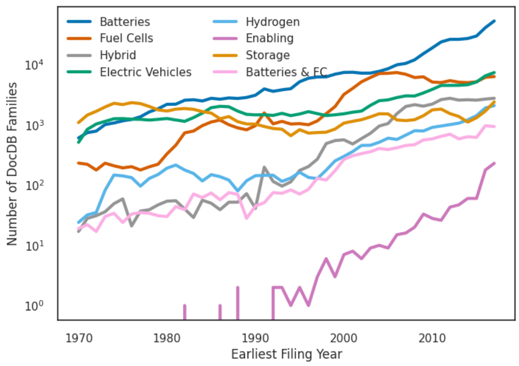
B.2 Patenting Trends at the Family Level



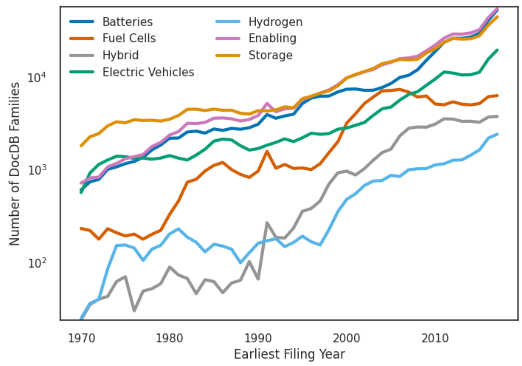
(a) Exclusive Classification (linear scale)



(b) Non-Exclusive Classification (linear scale)



(c) Exclusive Classification (log scale)

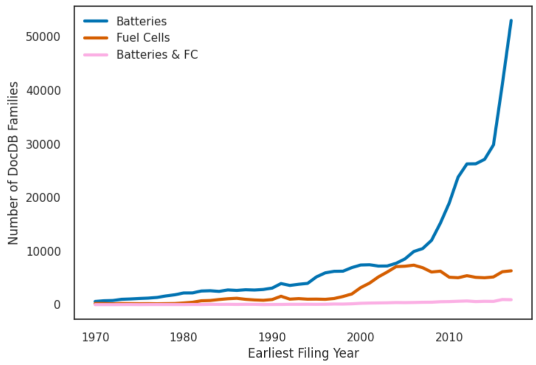


(d) Non-Exclusive Classification (log scale)

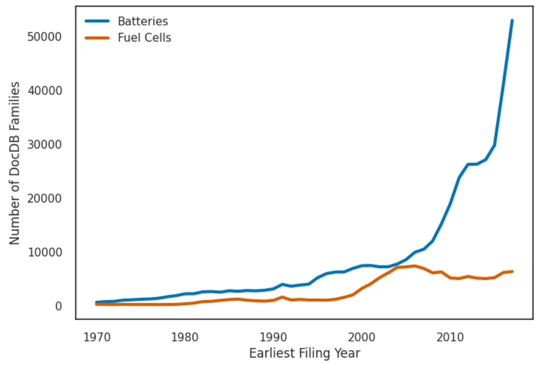
Figure SI2
Total Number of Clean Cars Patent Families in PATSTAT

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".

Linear Scale

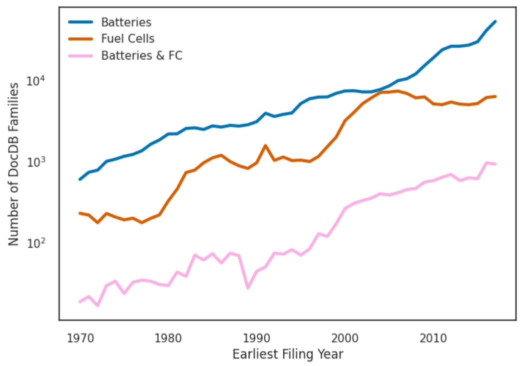


(a) Exclusive Classification

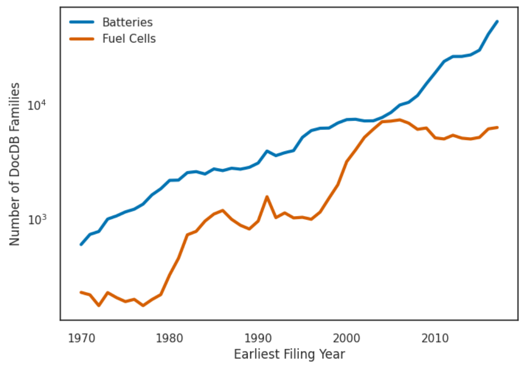


(b) Non-Exclusive Classification

Log Scale



(c) Exclusive Classification



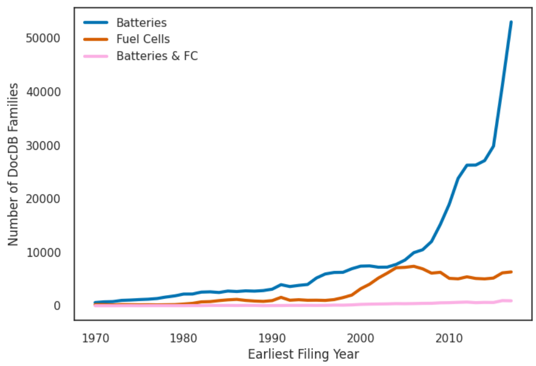
(d) Non-Exclusive Classification

Figure SI3
Total Number of Battery and Fuel Cells Patent Families in PATSTAT

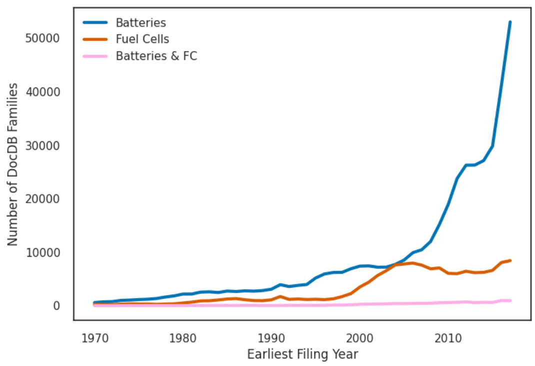
B.3 Including Hydrogen Patents under "Fuel Cell" Patents

The graphs below show that the inclusion of hydrogen patents in the "fuel cell" category results in a slight increase in the number of "Fuel Cell" patents. However, this adjustment does not significantly alter the overall trend observed in the data.

Linear Scale

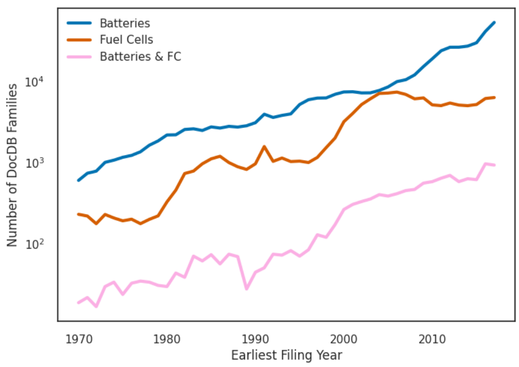


(a) Not Including Hydrogen Patents
(Same as Figure SI3a)

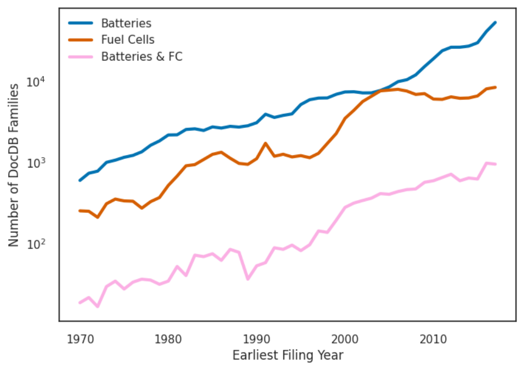


(b) Including Hydrogen Patents

Log Scale

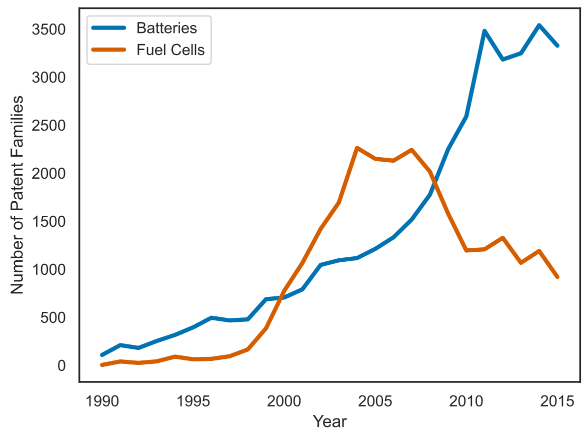


(c) Not Including Hydrogen Patents
(Same Figure as SI3c)

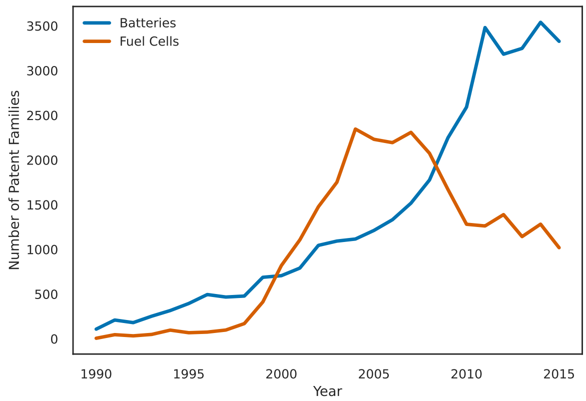


(d) Including Hydrogen Patents

Figure SI4
Total Number of Battery and Fuel Cells Patent Families in PATSTAT



(a) Not Including Hydrogen
(Same as Figure 2a)



(b) Including Hydrogen

Figure SI5
Figure 2a with and without including Hydrogen Patents under the Fuel Cell Category

B.4 Transport vs Non-Transport Applications of Battery Patents

In our methodology for classifying battery patents, we distinguish between those specifically related to transport applications and those that are not, guided by the codes listed in Table SI4. Codes falling under the categories B60 and Y02T are designated for transport-related patents. In contrast, the code Y02E60/10, which pertains to enabling technologies with potential contributions to GHG emissions mitigation, such as energy storage using batteries, is more broadly applicable and may encompass both transport and non-transport inventions. To categorize a battery patent family accurately, we apply a rule: if a patent family is associated with a B60 and Y02T subcode, it is classified as related to transport. Otherwise, it is considered non-transport.

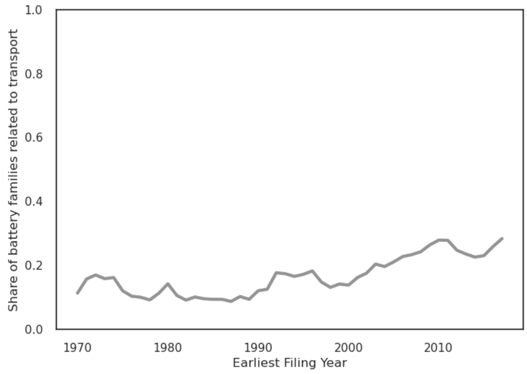
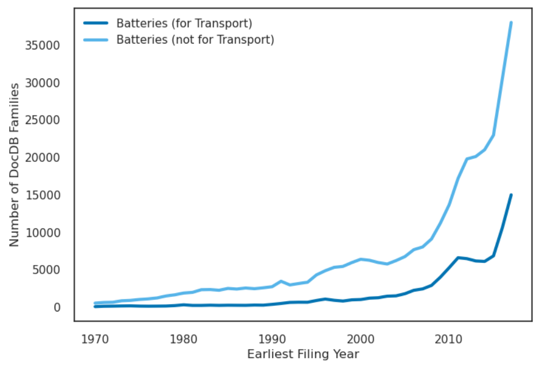
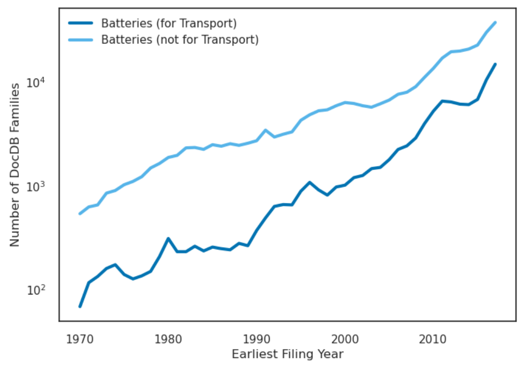


Figure SI6
Share of Transport-Related Battery Patent Families in PATSTAT

Note: This graph explores the split of battery patent families into transport and non-transport categories. Historically, transport-related patents constituted a minor fraction, around 10%, which saw an increase in the 1990s and 2008, peaking at approximately 28% by 2010.



(a) Levels



(b) Log

Figure SI7
Total Number of Transport and Non-Transport Battery Patent Families in PATSTAT

C Patenting Trends

C.1 Patenting Trends for Carmakers

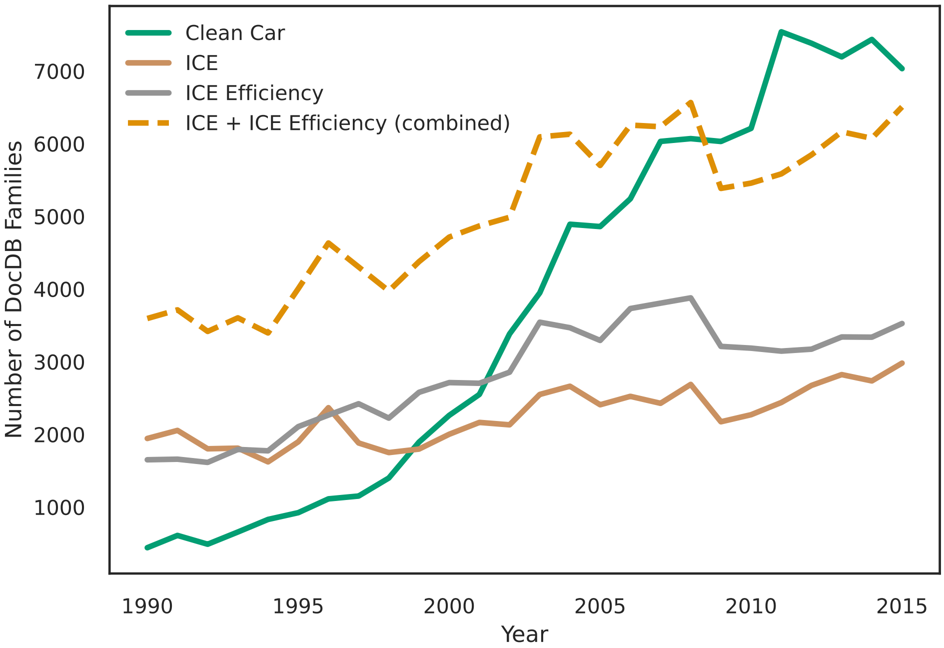
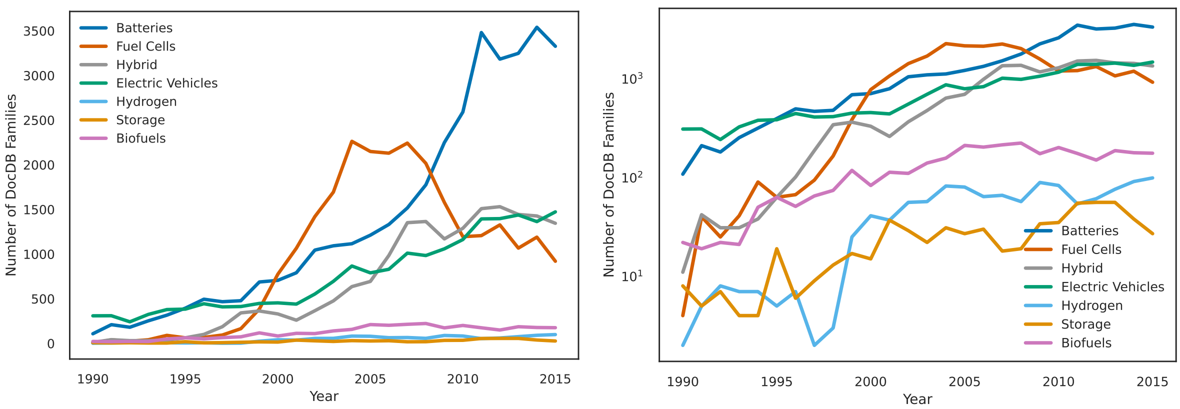


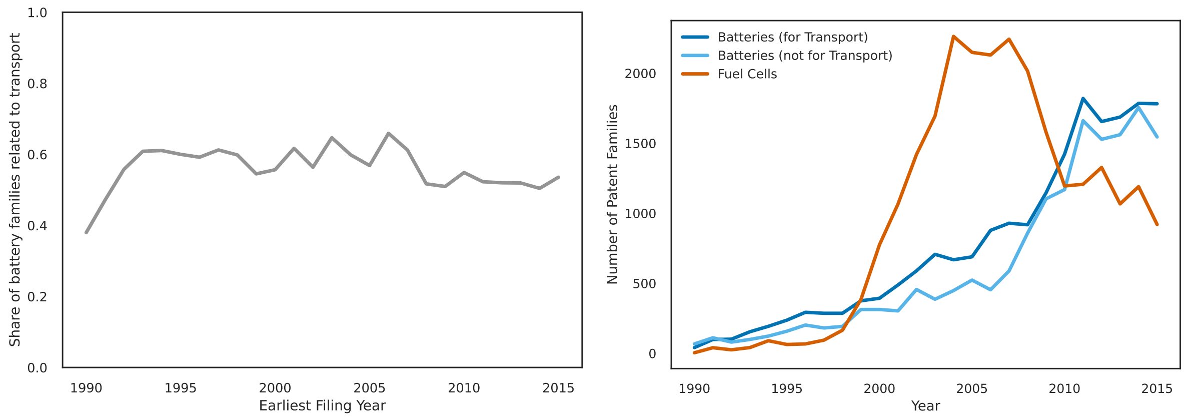
Figure SI8
Carmaker patenting on the ICE versus clean cars



(a) Linear scale

(b) Log scale

Figure SI9
Counts of Carmakers' patents by type of technology (log scale)



(a) Share

(b) Patent Family Counts

Figure SI10
Carmakers' Battery Patenting Related to Transport vs Non-Transport

Note: The figure reveals that 50 to 60% of battery patents filed by carmakers are transport-related—a stark contrast to the broader spectrum of battery patents (as shown in Subsection B.4). Temporal trends are very similar across transport and non-transport applications.

C.2 Sectoral Decomposition

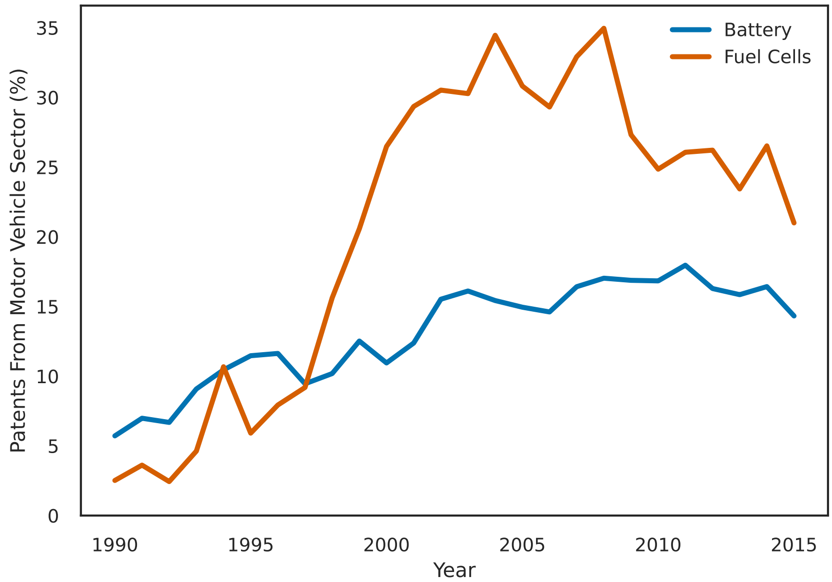


Figure SI11
Battery and Fuel Cell Patenting: Percentage of Motor Vehicles in Total

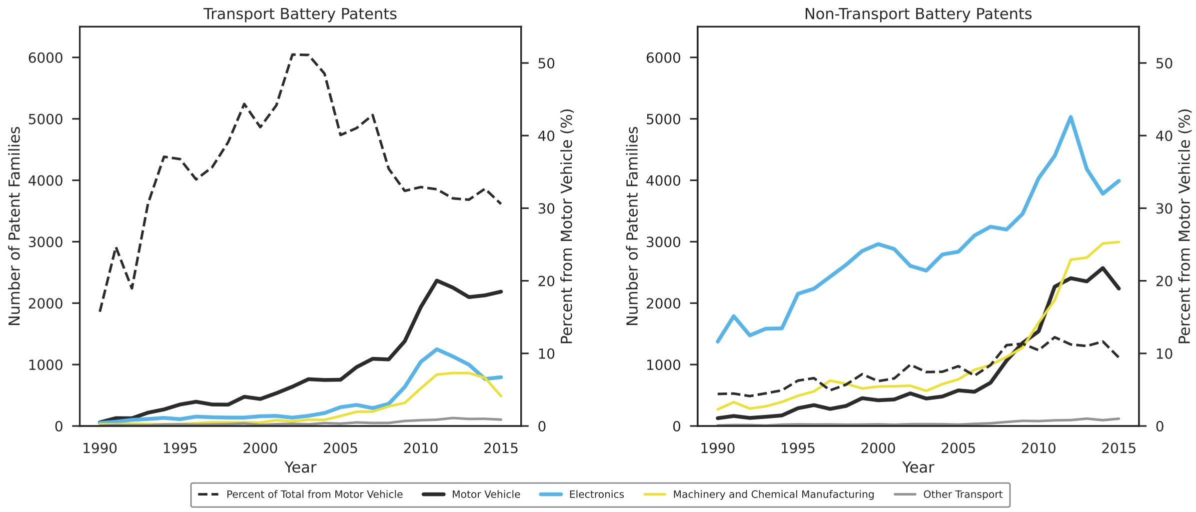


Figure SI12
Decomposition of Transport and Non-Transport Battery Patenting by Industry

Note: The figure shows identifies the motor vehicle sector as the primary contributor to transport-related battery patents, significantly outpacing the electronics, machinery, and chemical manufacturing sectors. Conversely, in the realm of non-transport patents, the electronics sector emerges as the dominant force, with the motor vehicle sector playing a lesser role.

C.3 Measuring Spillovers with Citations

C.3.1 Citation Flows

Following prior work, we use patent citations as a proxy for knowledge spillovers [1]. Figure SI13 plots the number of backward citations made by carmakers in their battery or FC families to non-carmakers. The figure shows that carmakers have been drawing more on the pool of knowledge outside of their industry than within, both for battery and FC. This highlights the importance of innovation trends in other sectors.

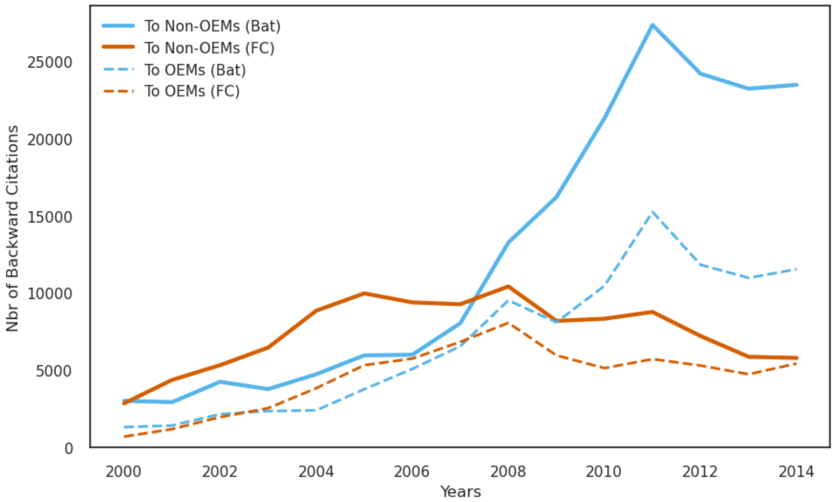


Figure SI13
Backward Citations made by Carmakers to other industries outside Motor Vehicles.
Note: The figure shows that carmakers have been drawing more on the pool of knowledge outside of their industry than within. This highlights the importance of innovation trends in other sectors.

C.3.2 Expected Spillovers

Figure SI13 also shows a significantly larger increase in the number of backward citations to non-carmakers for batteries compared to FC. However, it's important to note that the citation count in year t is influenced both by the *availability* of relevant non-carmaker patents in that year and by the *production* of carmaker patents making these citations in the same year. To remove the influence of carmakers' change in patenting and isolate the role of the *availability* of relevant non-carmaker patents in year t, we construct a measure of *expected* spillovers [2]. This measure does not scale with contemporaneous changes in carmakers' patenting and capture the potential of the available knowledge on batteries or FCs to be absorbed into carmakers' patents, independently from whether or not they patent.

We compute the *expected* spillovers of non-carmakers to carmakers for a particular technology k, say battery, as follows:

$$ExpectedSpillovers_t^k = \sum_{l=1}^{10} FamilyCount_{t-l}^{k,NonCar} \times AbsorptionRate_l^k. \tag{1}$$

$FamilyCount_{t-l}^{k,NonCar}$ is the number of families related to technology k filed by non-carmakers at $t-l$. It captures the flows of non-carmakers families from the past that are available to be cited. $AbsorptionRate_l^k$ is the rate at which non-carmakers families are being absorbed by carmakers within l years, or in other words, it is the number of times that a family filed by a non-carmaker get cited by a carmaker within l years. This rate is calculated as an average, for the whole period. Specifically:

$$AbsorptionRate_l^k = \frac{CitationCount_l^{k,Car\Rightarrow NonCar}}{FamilyStock_{2021-l}^{k,NonCar}} \tag{2}$$

$CitationCount_l^{k,Car \Rightarrow NonCar}$ is the number of citations made by carmakers to non-carmaker families within l years of the nonmaker family being filed. To calculate this quantity, we consider all families related to technology k filed by non-carmakers between 1990 and 2021 and analyse the timing of their forward citations to carmakers. $FamilyStock_{2021-l}^{k,NonCar}$ is the total number of families related to technology k filed non-carmakers between 1990 and $2021-l$. Hence, we divide by a measure of how many families existed and that could have been cited. This is a way of normalizing by the amount of available knowledge. Hence, the absorption rate is akin to a number of carmaker citations per available non-carmaker family.

Figure SI14 shows that expected spillovers for batteries dominate those for fuel cells over the whole period and especially after 2010. See note for more details.

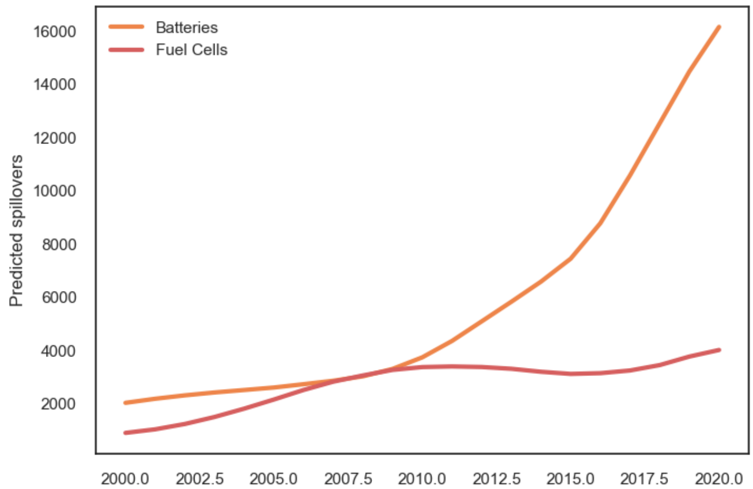


Figure SI14
Expected battery and fuel cell spillovers to OEMs from outside the industry.

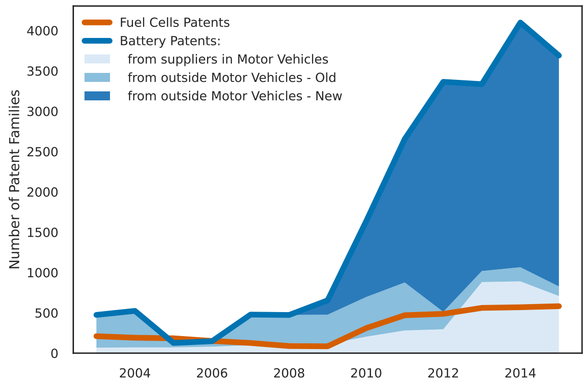
Note: The figure shows that expected spillovers for batteries outpaced those for fuel cells, particularly after 2010. This is the case even though fuel cells were absorbed at higher rates than batteries (i.e., $AbsorptionRate_l^k$ are higher). This might be because carmakers focused more on fuel cells before 2010 and because fuel cell research outside of car manufacturing might have been more aimed at transport uses. The figure suggests that carmakers were able to ride an external wave of battery innovations. For fuel cells, eventhough carmakers absorbed external knowledge, there was no wave of innovation that could sustain cross-sector learning.

C.4 Suppliers

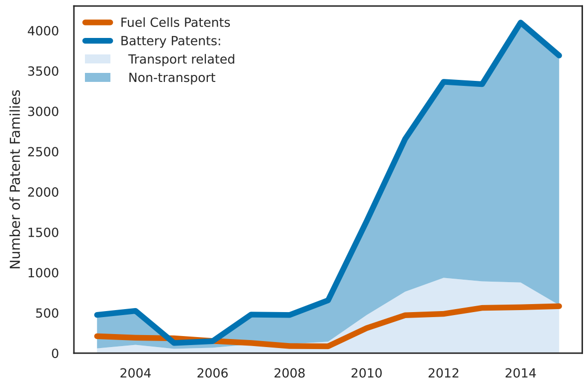
Table SI7
Top 10 New Suppliers

Name	Region	Battery Patent Concentration	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%

Note: The table provides descriptive statistics about the ten new suppliers that were responsible for the greatest number of battery patents between 2003 and 2017. Specifically, Column 3, "Battery Patent Concentration" is calculated as the ratio of the new supplier's count of battery patents filed between 2003 to 2017 to the total of all battery patents filed by any new suppliers. The top 10 suppliers based on this share are listed. Columns 4 and 5 display the average stock of battery patents and all patents, respectively, from 2003 to 2017, calculated cumulatively with a 20% annual discount. Column 6, "Nbr OEMs", indicates the number of distinct carmakers connected to each supplier at least once since 2009. Column 7, "% New Links", represents the proportion of new supplier-carmaker relationships post-2009 attributed to each supplier.



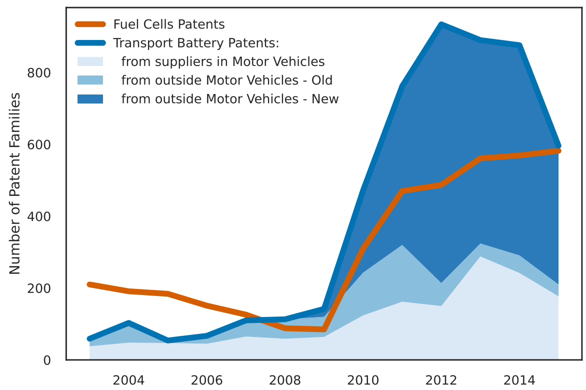
(a) By Type of Suppliers (Same as 4b)



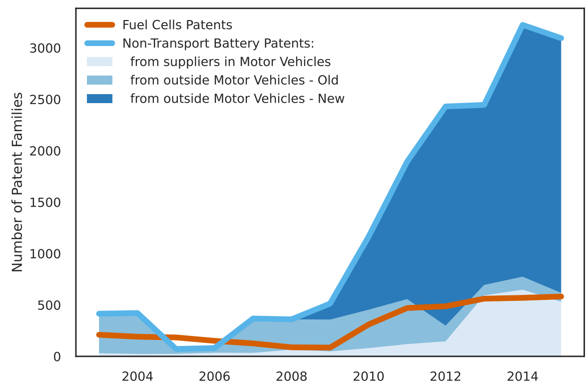
(b) By Type of Battery Families

Figure SI15
Patent Counts Decomposition of Active Suppliers

Note: The figure shows that the large increase in the total number of battery patents from active suppliers, is primarily driven by the non-transport category. This is consistent with the new suppliers, notably from the electronics industry, being intensely involved in patenting battery technologies, focusing more on applications beyond transport.



(a) For Transport Battery Families



(b) For Non-Transport Battery Families

Figure SI16
Patent Counts Decomposition of Active Suppliers By Type of Suppliers

Note: The figure provides a breakdown of the transport and non-transport battery patents from active suppliers, by type of supplier. This view confirms that both the large increase in non-transport battery patents and the more modes increase in transport battery patents originates from new suppliers.

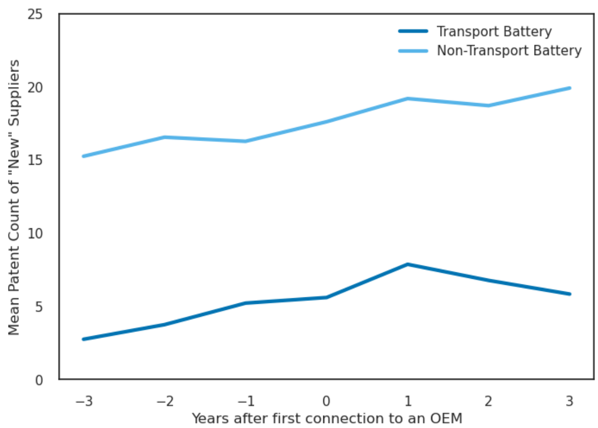
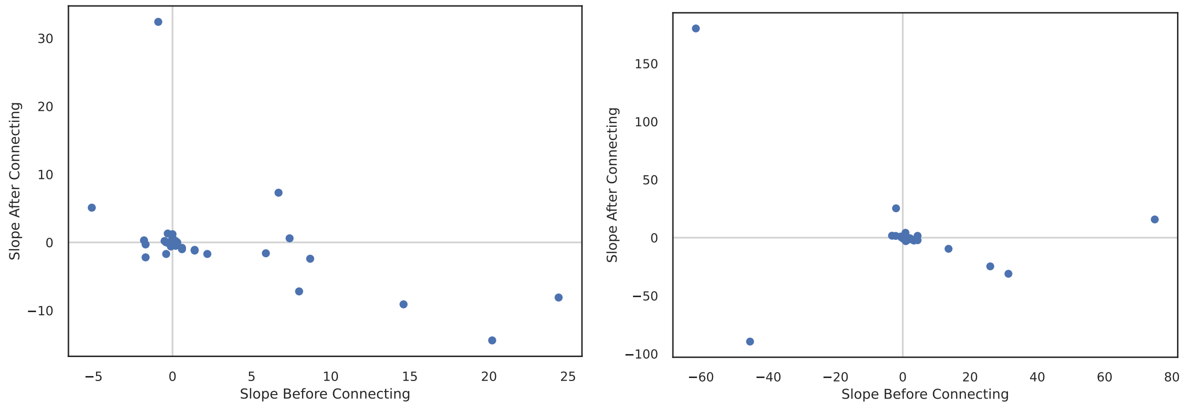


Figure SI17
Patenting of New Supplier Before/After Year of First Connection to Carmakers

Note: The figure displays the trend of battery patenting activity for the average new supplier, three years before and after their first connection to a carmaker. The period preceding a partnership seems to indicate a rise in battery patents,especially for transport-related innovations. However, post-collaboration, the focus on transport battery patents appears to stabilize or even diminish, although these trends are not statistical significant.



(a) For Transport Battery Families

(b) For Non-Transport Battery Families

Figure SI18
Pre- and Post-Trend For Each New Supplier

Note: The graphs explore the variability among new suppliers, with each dot symbolizing a unique supplier and axes representing the trend in patenting before and after connecting with carmakers. This analysis, based on regression of patent counts against years around the initial connection, highlights a cluster of suppliers showing no marked trend (observations that are close to zero on the graph). Notably, when significant trends are observed, they typically consist of positive growth in patenting activity prior to collaboration, followed by a plateau or decrease thereafter.

C.5 Carmakers' Citations Patterns

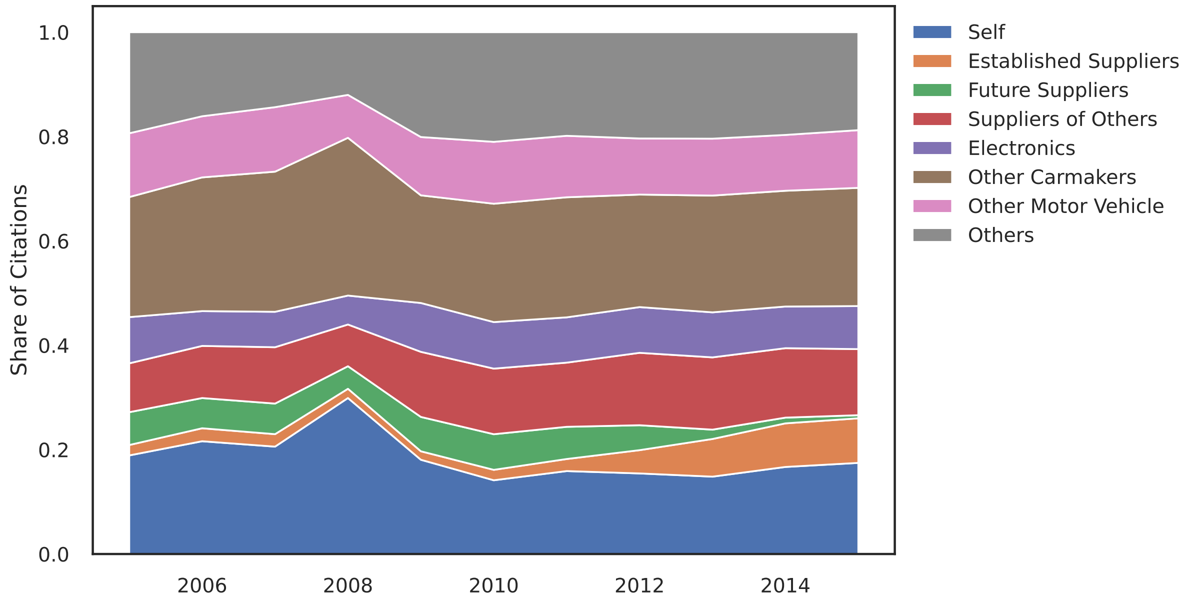


Figure SI19
Average Carmaker's Battery Families Backward Citations

Note: The graphs illustrate the types of firms cited in carmakers' battery patent families. Each patent family may be associated with multiple firms, and we categorize these citations hierarchically. First, we identify if a citation is to the carmaker itself ('Self'). If not, we determine if the cited patent is linked to the carmaker's suppliers, distinguishing between those with an existing relationship at the time of filing ('Established Suppliers') and those that will establish a relationship in the future ('Future Suppliers'). Next, we assess if the citation involves suppliers to other carmakers ('Suppliers of Others') or firms in the electronics sector. Subsequently, we check if the cited patent is linked to other carmakers ('Other Carmakers') and to firms within the Motor Vehicles industry ('Other Motor Vehicle'). Citations not fitting these categories are labeled as 'Other'.

We then aggregated the data at the level of carmaker and plot the distribution of citations for the average carmaker over time. The figure presents the data in "shares." Overall, there are no significant upward or downward trends observed. There is a modest decline in self-citations, and the green area gradually diminishes while the orange area expands. This transition is somewhat inherent to the methodology: green represents citations to future suppliers, so as time progresses, these suppliers become active, transitioning their citations to the orange area, which represents established suppliers.

On average, during the period analyzed, 18% of citations are self-citations and 24% are directed towards other carmakers, making these the two largest categories. Following these, citations to other suppliers account for 12%, to own suppliers for 9%, and to firms in the electronics sector for 8%. These descriptive statistics underscore the tendency of carmakers to cite their own suppliers and electronics firms in comparable proportions.

C.6 Citations to Hybrid

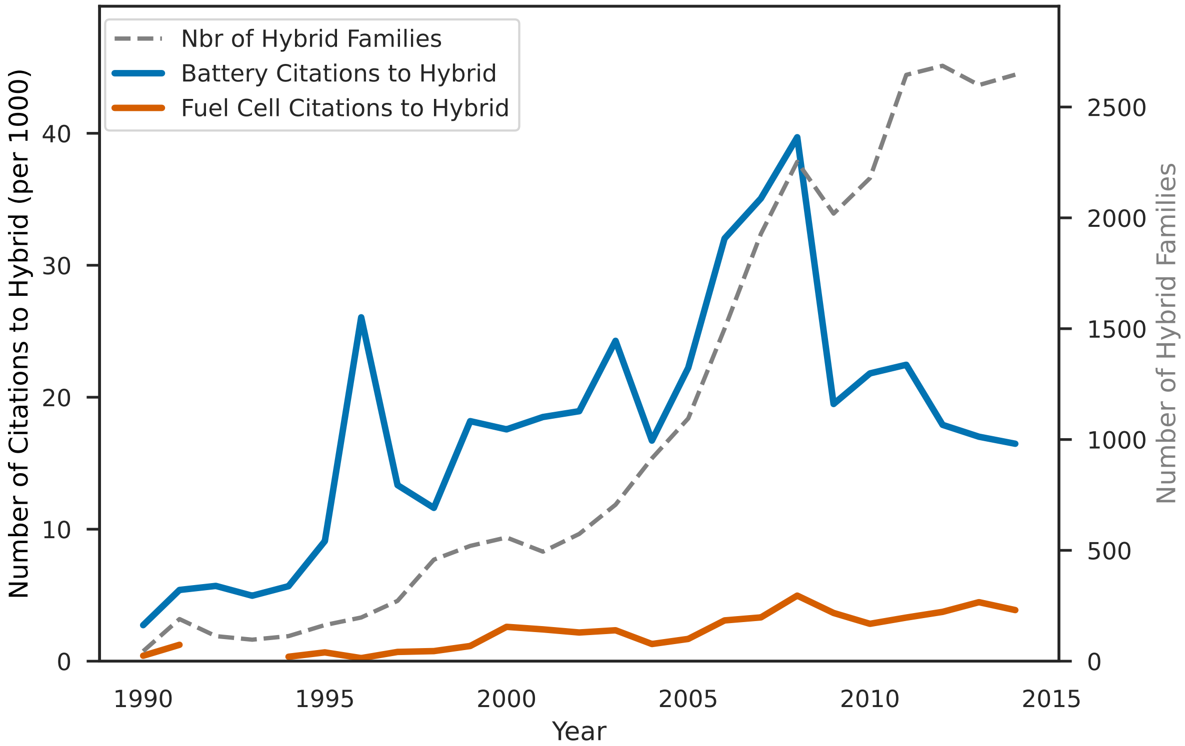


Figure SI20
Carmaker's Families Backward Citations To Hybrid

Note: The figure examines the spillover effects between Hybrid technologies and battery or FC. The dashed line represents the total number of hybrid patent families filed over time, while the blue and orange lines indicate the proportion of citations from BEV and FC patent families to hybrid families, respectively, per thousand citations. We see that as the number of hybrid patent families grows, citations from both BEV and FC inventions to hybrid technologies increase. However, BEVs cite hybrid technologies significantly more than FCs do. This trend may suggest that the advancement of hybrid technologies has been more beneficial to the development of BEVs than to FCEVs.

D Policy Data and Analysis

D.1 Strategic Orientation Policy Data

Table SI8 shows our final coding of strategic orientation of each country over time. This section provides more detail on our data collection and coding approach. First, in Section D.1.1 below, we explain how we identified and selected strategic orientation policies.

Then in Section D.1.2, we explain our rules for coding the technological focus of policies. We have added a table for each country (Tables SI9 to SI15) providing detail on each policy document, including the government body that published it and quotes from the referenced text that supports our coding decision. We also explain how we aggregated all these policies into a technological focus for each country-year, which yields Table SI8.

Finally, Section D.1.3 checks whether consumer incentives (tax credits or purchase grants) and infrastructure investments were targeting a specific technology in a way that may contradict our coding of strategic orientations; we find no major contradiction.

Table SI8
Technological Focus of Different Countries

Country	Period	Primary technology	Secondary technology
Japan	1976-1996	BEVs	
	1997-2000	All types	
	2001-2009	FCEVs	
	2010-2020	PHEVs, BEVs	FCEVs
China	1995-1999	All types	
	2000-2008	Equal focus on FCEVs, BEVs and HEVs	
	2009-2020	BEVs	FCEVs
South Korea	2003-2009	FCEVs	
	2010-2015	BEVs	
	2016-	BEVs	FCEVs
France	1992-1998	BEVs	
	1999-2008	No clear strategy	
	2009-2020	BEVs, PHEVs	
UK	2002-2017	All types (technology neutral)	
	2018-2020	BEVs, PHEVs	FCEV
Germany	2007-2008	FCEVs	
	2009-2020	BEVs	FCEVs
USA	1988-2000	Biofuels	Biofuels
	2001-2008	FCEVs	Biofuels
	2009-2015	PHEVs, BEVs	FCEVs, Biofuels
	2016-2020	no clear strategy	

D.1.1 Identifying Policies

We define strategic orientation policy as any policy that provides a framework or roadmap for the transition of the industry to alternative low-carbon technologies. The aim is usually to coordinate the expectations of relevant actors on medium to long-term goals, as well as on the sequence of needed investments. To be included in our analysis, they must be 1) forward-looking; 2) articulate a concrete vision of how the industry will change (which may be either qualitative or involve quantitative targets). They can arise from either the executive or legislative branches. We ignore sub-national policies.

To identify these policies, research assistants carried out literature reviews to identify all relevant transport policies and industrial policies targeted at the automotive industry over the period 1990-2020 in USA, UK, Germany, France, China, Japan and South Korea. These countries were chosen as the principal jurisdictions for carmakers that are active innovators. These literature reviews covered both the peer-reviewed and grey literatures. We subsequently also checked the IEA's Policies and Measures Database[1] and the Climate Change Laws of the World database.[2] The research assistants then coded policies as being either consumer incentives, R&D funding programs, production subsidies, procurement, infrastructure investments, standards or strategic orientation.

Of course, strategic orientations often come along with various incentives to consumers and producers. However, we refrain from inferring a strategic orientation from the design of these incentives. The reason is that we conceptualize strategic orientations as fulfilling a distinct role from that of incentives. Strategic orientation policies clarify the direction of travel, coordinating the expectations of relevant actors. In contrast, an incentive program may be put in place to encourage clean car purchases or R&D in clean car technologies without articulating a strategic plan for the transition of the industry. Likewise, a strategic plan may be articulated without concomitantly committing resources to subsidy programs. To code the technological focus of strategic orientation plans, we thus focus on policy documents that articulate these strategic plans and do not infer a strategic orientation from the design of subsidies.

D.1.2 Coding the Technological Focus of Strategic Orientations

For each strategic orientation policy, we read the text of the policy when it was available, or accounts by other authors that discuss these policies when we could not find the text of the original policy. Each line of Tables SI9-SI15 refers to a given policy and a reference text. For each strategic orientation policy, we code the following information:

- Technological focus: this is the main information of interest. If a reference text indicates that the policy has the explicit aim of furthering a *specific* clean vehicle technology, then we code this as the technological focus of the policy. A policy can have multiple technological foci. In particular, we allow for a "Primary Technology" and a "Secondary Technology" if one technology is given priority over another. For example, in the later periods, most governments express the goal of transitioning to BEVs but say they will continue to support FCEVs as a long-term option or goal. In this case, we code FCEVs as the Secondary Technology. *The tables also provide the text in each reference that determined our coding.*

[1] For more information, see `https://www.iea.org/policies/about`.

[2] For more information, see `https://climate-laws.org/`

- The government body from which the policy originated
- Time period: we code this as the year the policy was published with an unknown end (e.g. 1990−) when the policy doesn't have an explicitly targeted period with an end. We code the end date when the latter is explicit (e.g. China's 5 year plans).

Having coded each policy, we proceed to define periods over which the technological focus is constant (or equivalently, coding the technological focus of each year in each country), to obtain Table SI8. 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.

An ambiguity can arise when a policy with no explicit end date is then followed by a policy with a different technological focus. For example, Japan's *Alternative Energy Technology Development Program* published in 2001 and focusing on FCEVs with no explicit end date seemingly collides with the 2010 *Next-Generation Automotive Strategy* focusing on BEVs. In most cases, these policies arise from the same government body (in this case MITI later renamed METI), and are not set in law. In such case, we consider that a new policy replaces the older one.

The USA is the only country presenting some exceptions to this rule. First, the Alternative Motor Fuels Act of 1988 sets a framework to rapidly expand the production of biofuel-powered vehicles and has no clear end date. It is clear that the focus has shifted since then, with the Bush Administration's push on hydrogen and FCEVs, and the subsequent push by the Obama Administration towards BEVs. Nonetheless, the Act still stands, and all legislation relating to energy since then has continued to include biofuels as part of the fuel mix for transport (we do not include here all relevant legislation as our focus is on FCEVs and BEVs). We thus code Biofuels as a Secondary Technology in SI8.

Second, the Trump Administration had no policy regarding clean vehicles (except for reducing DOE's budgets for clean energy and clean vehicles). We thus coded this period as having no clear strategy, even though the American Recovery and Reinvestment Act of 2009 was still in effect and some of its spending still on-going. This is because the ARRA is a spending bill, whose role as a strategic orientation policy should be understood in the context of the Obama Administration's other clean transport goal setting initiatives.

D.1.3 Robustness Check: Technological Focus of Consumer Subsidies and Infrastructure Investments

We have defined strategic orientation as policies that explicitly articulate medium to long-term objectives for changing to a new technology in the industry. In coding strategic orientation, we thus set aside other types of policies that could signal a clear technological focus. Chief among these are infrastructure investments, as infrastructure is clearly either geared at BEVs or FCEVs and provide a long-term commitment due to the longevity of such investments. We thus checked if there is any *contradiction* between our coding of strategic orientation and infrastructure investments. Additionally, we also checked for contradictions between our coding of strategic orientation and the technological focus, if any, of consumer subsidies.

- China: Prior to 2010, China's consumer incentives were targeted at all types of clean car technologies (Ten Cities Thousand Vehicles policy). After 2010, they focused on BEV and PHEVs. Investments in charging infrastructure starts in 2009 with budgeting as part of the Auto Industry Adjustment and Revitalization Plan. There is thus no contradiction with our coded strategic orientation.

- Japan: A first consumer incentive program targeting BEVs was introduced in 1996, with the Clean Energy Vehicles Program. Subsequently, consumer incentives were based on a neutral criterion (vehicles exceeding the fuel efficiency standard). Again in 2015, technology specific subsidies targeted both BEVs and FCEVs. Some investment in charging infrastructure for BEVs occurred in 1993 and this picked up again after 2010. These policies do not contradict our coding of strategic orientation.
- South Korea: Consumer incentives in South Korea start in 2009, targeting HEVs and BEVs as part of the Green New Deal. FCEV subsidies started in 2019. Charging infrastructure investments started in 2015, while hydrogen charging investments started in 2020.
- USA: Consumer tax credits for HEVs, FCEVs and biodisel in the Energy Policy Act of 2005, while the Energy Independance and Security Act of 2008 extended to BEVs, PHEVs. Infrastructure investments start in 2009 for EV charging. Here again, we note no contradiction with the coding of strategic orientation.
- France: A first subsidy scheme was introduced in 1995, favoring BEVs. In 2007, the Bonus/malus system was introduced, based on vehicle efficiency (and in some periods, targeted at BEV/PHEV specifically). Infrastructure policy started in 2010, focusing on the charging network for BEVs. There is thus no contradiction.
- Germany: Subsidies started in 2016, and cover all main technologies (BEV, FCV and PHEV), while infrastructure investments started in 2014 targeting fast charging, with more recent investments for hydrogen.
- UK: Infrastructure investments start in 2011 with the Plugged in Places program, mostly focused on BEVs, with a small amount for demonstration hydrogen chargers 2014-2018. Consumer tax incentives exist that are tech neutral (excise duty calibrated to emissions), and a BEV/PHEV car grant was introduced in 2011. This contradicts to some extent the technology neutral stance in the strategic orientation. This technology neutral stance becomes increasingly rhetorical over the years, as the UK needs to align its policy with that of other countries.

Table SI9
China's strategic orientation policies

Policy name	Period	Government body	Primary technology	Secondary technology	Reference	Evidence from the document
9th FYP	1996-2000	CCP Central Committee; China's National People's Congress	All types		Gong *et al.* [3]	NEV-related work began much earlier—in fact, in the 1990s [. . .] At the beginning, there was no clear policy preference. Then hybrid technology became a high interest, mainly due to the introduction of the Toyota Prius and other hybrid products in the late 1990s and during the 10th FYP period" "The 9th FYP (1995–2000) had two major developments for BEVs. One was to formally highlight the importance of BEVs by adding BEVs into the National Key Science & Technology Industrialization Projects (National Electric Vehicle Test and Demonstration Zone 2004). The other development was the Clean Vehicle—Clean up the Air Program that was launched by 13 ministries together in 1999 (MOST 1999; MOST et al. 1999). In this program, clean vehicles covered a broad area, including clean conventional internal- combustion engine vehicles, compressed natural gas vehicles (CNGVs), liquefied petroleum gas vehicles (LPGVs) (two alternative fuel vehicles), HEVs, and BEVs. During this FYP, an EV test and demonstration zone was established in Shantou, Guangdong Province, and an EV standard technical committee was set up to lead EV standard development.
10th FYP, including the Electric Vehicle Special Project and the National High-Tech R&D Program (863 Program)	2001-2005	CCP Central Committee; China's National People's Congress; MOST	Equal focus on FCEVs, BEVs and HEVs		Gong *et al.* [3]	Fig.3: Within these five years, China specified and established R&D focuses on three electric drive technologies (fuel cell, electric, and hybrid vehicles) and three associated technology components (battery, electric motor, and electric control system) and successfully developed several FCV, BEV, and HEV prototypes.
					ICCT [4]	Figure ES1 - As a result, in 2001, new energy vehicles were incorporated into the 863 Project for the 10th Five-Year-Plan (FYP), China's primary national planning document. China also developed its first new energy vehicle technology roadmap, the Three-by-Three Research and Development Strategy. It included three new energy vehicle technologies as pillars—fuel cell, hybrid, and electric—and three component technologies: powertrain control systems, driving motors, and batteries. These guided China's new energy vehicle development for the next 15 years.
11th FYP	2006-2010	CCP Central Committee; China's National People's Congress; MOST; NDRC	Equal focus on FCEVs, BEVs and HEVs		Gong *et al.* [3]	The most recent five years (the 11th FYP, 2006–2010) established a milestone for NEV development in China by moving NEVs from the laboratories or prototypes to the market and road in a large volume.[. . .] The Management Rule on New Energy Vehicle Production, adopted by the NDRC (the National Development and Reform Commission) in 2007, officially defined the term, NEV, for the first time. Based on the definition, NEVs include HEVs, BEVs (including solar-panel-powered vehicles), FCVs, hydrogen internal-combustion engine vehicles, and other vehicles with new fuels, such as di-methyl ether and high-efficient energy storage capacitors
					ICCT [4]	In the 11th FYP, the 863 Project's new energy vehicle program escalated in size and scope, and more regions and industry players joined"[. . .]"Also during the 11th FYP, China sought to move new energy vehicles from the laboratory, research and development (R&D), and demonstration phases to production. In 2007, the National Development and Reform Commission (NDRC) released the Management Rule of New Energy Vehicle Product Market Entrance (2007), which defined and stipulated the terms and criteria for mass producing new energy vehicle products"(noting the broad definition of NEVs - see above).
China Science and Technology Medium- and Long-Term Development Plan	2006-2020	State Council	Equal focus on FCEVs, BEVs and HEVs		Gong *et al.* [3]	for the first time mentioned the NEV term in the official policies and specified focusing on hybrid vehicles, alternative fuel vehicles, and fuel cell vehicles (the State Council 2006).
					State Council [5]	p21: Priorities will be assigned to research on and development of key technologies for design, integration, and manufacturing of hybrid, alternative fuel, and fuel cell automobiles, power system integration and control technologies, automobile computation platform technologies, and technologies for high-efficiency and low-emission internal combustion engines, fuel cell engines, accumulator batteries, driving motors, and other critical components, and technologies for developing experiment and test techniques and infrastructure for automobiles using new energy.
Auto Industry Adjustment and Revitalization Plan	2009-2011	State Council	BEV, HEV	FCEVs	ICCT [4]	p3: The State Council, China's powerful cabinet, provided another push in March 2009 by issuing the Auto Industry Adjustment and Revitalization Plan (State Council, 2009). The plan set forth China's first official goal for massive new energy vehicle deployment: to reach production capacity of 500,000 battery, plug-in hybrid, and hybrid electric vehicles

Continued on next page

Table SI9 – continued from previous page

Policy name	Period	Government body	Primary technology	Secondary technology	Reference	Evidence from the document
					Gong *et al.* [3]	From the technology aspect, hybrid vehicles definitely were the mainstream technology before 2009. After that, impacted by the national policy direction shift to BEVs, the BEV models became popular. Several FCV models are certified for demonstration, but the number is quite small. Only 14 models are certified, mainly because of support to the Shanghai 2010 World Expo. The FCV demonstration also occurred before 2010, such as for the 2008 Olympic Games, and some updated versions of those previously demonstrated models have been included in the recommended NEV model bulletin.
Accelerating the Cultivation and Development of Emerging Strategic Industries	2010	State Council	BEV, HEV		Gong *et al.* [3]	In order to help China adjust its economic structure toward resource savings and move in an environment friendly direction, and recognizing the strategic impacts of NEVs on the auto industry in the future, the State Council issued Decisions on Accelerating the Cultiva- tion & Development of Emerging Strategic Industries in October 2010, and it selected NEVs as one of the seven strategic industries. In the policy, plug-in hybrid and pure electric vehicles were further highlighted as the focus for demonstration and commercialization (the State Council 2010).
12th FYP	2011-2015	CCP Central Committee; China's National People's Congress	BEVs		CCPCC [6]	This is the overall 12th FYP: P8: Automobile: Build a system for principle, production and industrialization innovation. Focus on management and control systems for power batteries, driving motors, and other key parts and power assemblies. Promote high-efficiency internal combustion machines, high-efficiency driving, light-weight materials and structures, complete vehicle optimization, ordinary hybrid power technologies, and the energy conservation of automobile products.
					MOST [7]	This is the 12th FYP for Electric Vehicle Technology Development. The document is in Chinese but excerpts translated on Asia Pacific Energy Info Portal show a principal focus on BEVs
Energy-Saving and New Energy Vehicle Development Plan	2012-2020	State Council	BEVs		ICCT [4]	In 2012, the State Council published the Energy-Saving and New Energy Vehicle Development Plan (2012–2020); it targeted the annual production and sale of 500,000 plug-in electric vehicles by 2015, rising to 2 million by 2020, and bringing cumulative new energy vehicles to 5 million by the end of 2020 (State Council, 2012).
					APEC [8]	The Electrified propulsion will be the main development strategy, focusing on the industrialization for EVs and Plug-ins

Note: Acronyms – MOST : Ministry of Science and Technology; NRDC: National Development and Reform Commission (department of the State Council serving as a macroeconomic management agency).

Table SI10
France’s strategic orientation policies

Policy name	**Period**	**Government body**	**Primary technology**	**Secondary technology**	**Reference**	**Evidence from the document**
Accord-cadre sur le developpement du vehicule electrique	1992-1999	Ministry of Industry + Ministry of Environment, Interministerial Group for Evs	BEVs		Calef & Goble [9]	”An initial protocol, the 1992 Accord-Cadre sur le Developpement du Véhicule Electrique, coordinated by the Ministry of Industry, the Ministry of the Environment, EDF, PSA (a consortium formed by Peugeot and Citroen), Renault and the government agency Groupe Interministériel Véhicules Electriques (GIVE, 199239.) considered EVs a timely instrument to reduce pollution and noise in French cities as well as CO2 emissions in French cities (GIVE, 1992). The signatories pledged that within three years the automobile companies would manufacture thousands of EVs and EDF would build the appropriate charging infrastructure.”
French inter-ministry committee for clean vehicles (CIVP)	1999-	Interministerial committee	No clear strategy		CIVP [10]	p4: This committee, chaired by the Ministère de l’aménagement du territoire and the Ministère de l’Environment and whose secretariat is provided by the State Secretariat for Industry, brings together all the administrations concerned, ministries responsible for transport, research, interior, finance, as well as the interministerial group on electric vehicles (GIVE). Its mission, according to the terms of its mandate, is to constitute ”a tool for analysis and proposals aimed, for LPG, CNG, electric, hybrid and fuel cell vehicles, at harmonizing public efforts, at informing , or to propose actions to the administrations concerned, in terms of industrial and technological development, legal, regulatory and fiscal framework and public intervention.”
					CIVP [11]	2003 report showing that the committee continues to monitor the development of all technologies, domestically and abroad
					CIVP [12]	2005 report showing that the committee continues to monitor the development of all technologies, with a new interest in the potential of biofuels
Plan national pour le développement des véhicules électriques et hybrides rechargeables (Plan Véhicules Décarbonés)	2009-	Ministry of Sustainable Development	BEVs		Assemblée Nationale [13]	p29: the 14 objectives of the plan show that it is exclusively focused on BEVs
					Actu de l’Environnement [14]	Summarises the overall objective for the 2020 Horizon: 2 million EVs by 2020
Pacte Automobile	2009-	Government	BEVs		Elysée [15]	p4: One of the major objectives is to bring out France a sector for batteries and the traction chain for hybrid vehicles and electric vehicles.

Table SI11
Germany’s strategic orientation policies

Policy name	Period	Government body	Primary technology	Secondary technology	Reference	Evidence from the document
National Innovation Programme Hydrogen and Fuel Cell Technology	2006-	BMWi	FCEVs		Bonhoff [16]	”To support and to accelerate the market preparation of technologies in the field of road transportation, the NIP focuses on deploying and demonstrating hydrogen vehicles and the associated infrastructure within its lighthouse project Clean Energy Partnership (CEP)”
National Electromobility Development Plan	2009-	BMWi; BMVBS; BMU; BMBF	BEVs	FCEVs	Bundesregierung [17]	”The aim of the National Electromobility Development Plan is to speed up research and development in battery electric vehicles and their market preparation and introduction in Germany. [...] The German Federal Government is looking to have one million electric vehicles on the road by 2020. [...] Plug-in and battery electric vehicles, which are included in the Development Plan, are the first choice for energy efficiency. [...] In pursuance of the Integrated Energy and Climate Plan, the National Electromobility Development Plan is concerned with battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV), including range-extended electric vehicles (REEV) [...] The National Electromobility Development Plan envisages the development and promotion of a concerted strategy with the collaboration of science, industry and government, from basic research to market entry. It encompasses the whole supply chain from materials, components, cells and batteries to the entire system and its application. It also provides for devising a scheme to integrate the additional power demand generated by electromobility into the grid, link this demand with renewable energy sources and use electromobility to contribute to grid load management. This will ultimately position Germany as a lead market for electromobility and enhance the long-term competitiveness of the motor-vehicle manufacturing and parts supply sector as one of the major pillars of national industry. [...] In the assessment of the German Federal Government, battery and fuel cell technologies are mutually complementary paths that need to be pursued together.”
					BMU [18]	Promotion of electromobility: It is aim of the federal government to develop Germany into a leading market for electromobility and a leading supplier of electromobility. The goal is to have one million electric vehicles on Germany’s roads by 2020, rising to six million by 2030. Measures to achieve this are currently being implemented under the government electromobility programme of May 2011.

Note: Acronyms – BMWi: Federal Ministry of Economic Affairs and Energy BMVBS: Federal Ministry of Transport Building and Urban Affairs; BMU: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety; BMBF: Federal Ministry for Education and Research

Table SI12
Japans's strategic orientation policies

Policy name	Period	Government body	Primary technology	Secondary technology	Reference	Evidence from the document
Electric Vehicles Market Expansion Plan	1976-1986	MITI	BEVs		Åhman [19]	The MITI established a basic market expansion plan for BPEVs in 1976 (MITI, 1990). This plan (and the following revised versions) was a comprehensive commercialisation plan coordinating government agencies, companies and municipalities in their efforts to expand BPEV development. Barriers were identified and the relevant actors were called upon to make efforts to remove these barriers through technical development, amending laws and taxes, creating new standards and building a fuel infrastructure.
Electric Vehicles Market Expansion Plan	1991-1997	MITI	BEVs		Åhman [19]	As a consequence, a third and more aggressive market expansion plan for BPEVs was issued by the MITI in 1991. The goal was then to have 200,000 BPEVs on the road by the year 2000.
Electric Vehicles Market Expansion Plan	1997-2001	MITI	All types		Åhman [19]	In 1997 the MITI altered the third expansion plan from 1991 to include not only BPEVs, but also HEVs, CNGVs, methanol-fuelled vehicles and FCEVs under the definition of Clean-Energy Vehicles (JEVA, 2002).
The Alternative Energy Technology Development Program	2001-	MITI, NEDO	FCEVs		Nakui [20]	The main purpose of this program is the development and commercialisation of PEFCs. [...] The program stipulates numerical targets of fuel cell electric vehicles diffusion as 50k cars in the year 2010 and 5M cars in 2020.
Policy Study Group on Fuel Cell Commercialization	2001-2010	MITI, supported cross-ministerially by the Fuel Cell Project Team of Senior Vice Ministers	FCEVs		Åhman [19]	In 2000, the Policy Study Group for Fuel Cell Vehicles drafted a plan for fuel cell commercialisation organised by the MITI/METI, see METI (2001). The methodology used is similar to that in previous BPEV expansion plans, thus including manufacturers, government and other possible actors. The plan presents a common vision for future FCEVs and coordinates activities such as R&D, infrastructure, demonstration and standards, among stakeholders. The study group expects the introduction phase to be between 2005 and 2010, when 50,000 fuel cell vehicles will be introduced in public utilities and FC-related companies. The target for the year 2020 is 5,000,000 sold FCEVs (METI, 2001). When the power of the ZEV Mandate gradually decreased towards the end of the 1990s, BEV production stopped. FCVs became the main target for policymakers, partly as a replacement for the unsuccessful BEVs; more about this in Section 5.3.
					Hikima *et al.* [21]	Fuel cell projects were adopted as part of the Prime Minister-led Millennium Project. The "Fuel Cell Commercialization Strategy Study Group" was established in METI in 2000. In 2001, fuel cell technology was assigned as a priority area in the Science and Technology Basic Plan, the sectoral promotion strategy, and the industrial technology strategy of the Japanese government
					Ishitani & Baba [22]	in December 1999 METI set up the Policy Study Group on FC Commercialization as an advisory committee on PEMFCs for automotive and stationary use for the director-general of the Agency of Natural Resources and Energy. The group consists of representatives from universities, automobile, electric and electronic manufacturing industries, NGOs, the media, energy industries (electricity and gas utilities), industrial associations, related non-profit organizations, national institutes and membrane manufacturers. After a year of intensive discussions and consulting with various related industries and organizations, including the US Department of Energy (DOE), DaimlerChrysler, General Motors and Ballard, the committee **issued its intermediate report in January 2001**, including a strategy for FC R&D in Japan. It also identified short-term and long-term scenarios and three development phases. The approach can be summarized as: 1) scenario setting for FC realization and RD&D planning through development phases and a short- to long-term strategy; 2) base preparation and technology verification (until 2005); 3)initial introduction (2005–2010); 4) penetration (after 2010); 5) role of government, industry and research
Next-Generation Automotive Strategy 2010	2010-2030	METI	PHEVs, BEVs	FCEVs	METI [23]	p16 shows the targets, putting Evs first. The rest of the presentation shows how the strategy is centered around removing barriers to commercialization for Evs.
2014 Automobile Industry Strategy	2014-2030	METI	PHEVs, BEVs	FCEVs	METI [24]	The targets are the same as in the 2010 strategy, as seen on page 22 of the report
Interim report of the Strategic Commission for the New Era of Automobiles	2016-2030	METI	PHEVs, BEVs	FCEVs	METI [25]	Technology targets on page 8 of the presentation Page 20: Hydrogen and FCEV long-term plan Page 23: Goals of the Automobile Strategic Committee are centered on solving the problems surrounding BEV introduction

Continued on next page

Table SI12 – continued from previous page

Policy name	Period	Government body	Primary technology	Secondary technology	Reference	Evidence from the document
Basic Hydrogen Strategy	2017-	Prime Minister's Office		FCEVs	Ministerial Council on Renewable Energy, Hydrogen and Related Issues [26]	The roadmap seeks to realize a hydrogen-based society on a step-by-step basis[...]: Phase 1: Dramatic expansion of hydrogen use By expanding the use of fixed fuel cells and fuel cell vehicles (FCVs) dramatically, Japan will capture the global market for hydrogen and fuel cells in which it leads the world. Phase 2: Full-fledged introduction of hydrogen power generation and establishment of a large-scale hydrogen supply system (by the second half of the 2020s) While increasing hydrogen demand further, Japan will increase the scope of current hydrogen sources to cover unused energy sources and establish a new secondary energy structure including hydrogen in addition to traditional electricity and heat. Phase 3: Establishment of a CO2-free hydrogen supply system on a total basis (by around 2040) Japan will combine hydrogen production with CCS or use hydrogen from renewable energy to establish a totally CO2-free hydrogen supply system. ⇒ FCEVs are considered a market to help the development of fuel cells and stimulate hydrogen demand as part of an economy-wide strategy.

Note: Acronyms – MITI (later METI): Ministry of Investment (later Economy), Trade and Industry; NEDO: New Energy and Industrial Technology Development Organization.

Table SI13
South Korea's strategic orientation policies

Policy name	Period	Government body	Primary technology	Secondary technology	Reference	Evidence from the document
10-Year National Plan for Energy Technology Development	2003-2010	MOTIE	FCEVs		Leflaive [27]	p8: The 10-Year National Plan for Energy Technology Development, released in 2003, selected fuel cells, photovoltaic (PV), wind power as high-priority areas.
Masterplan for the Realisation of Hydrogen and New Renewable Energy Economy	2005	MOTIE	FCEVs		Kang & Park [28]	Through a series of steps, hydrogen fuel cell vehicles were set squarely in the middle of a governmental effort to promote alternative fuel vehicles
					Outlook on Hydrogen Economy & Roadmap - Korea [29]	The first comprehensive hydrogen economy vision of Korea dates back to September 2005 when Ministry of Trade, Industry and Energy (MOTIE) announced the 'Masterplan for the Realisation of Hydrogen and New Renewable Energy Economy'. The early 2000s was characterised by optimism around the hydrogen economy and the plan's goals were ambitious: the production target of fuel cell vehicles (FCEVs) by 2020 was 2 million units,
Hybrid and Fuel-Cell Powered Vehicles Plan	2005-2010	MOTIE	FCEVs		Leflaive [27]	p15: A five-year plan, developed by MKE, would allow the country to develop its own hybrid car technologies and test-drive fuel cell cars by 2010. Consumers who buy hybrid vehicles would be offered various incentives such as subsidies, tax breaks, and discounted parking fees. In addition, to further promote the use of hybrid vehicles, government agencies will purchase hybrid cars for official use.
Green Car Promotion Strategy (also translated as "Green Car Power Development Roadmap")	2010-2016	Presidential Comission on Green Growth	BEVs		Hwang [30]	In 2010, the green car road map was released for reducing GHG. According to that plan 1 million BEVs should be provided by 2020.
					Lee & He [31]	In 2009, the Korean government proclaimed the vision of "the powerful EV nation" and proposed a roadmap for the gradual implementation of advanced EV technology development, demonstration and diffusion projects. In the 'Green Car Power Development Roadmap' announced in 2010, policies for industrial development such as green car technology development, mass production, expansion of supply base, and industry innovation were suggested.
Green Car Industry Stimulation Plan		MOTIE	BEVs		Hwang [30]	Korean government announced the Green Car Industry Stimulation Plan with intensive preparation over six months. The vision of that plan is for the nation to become one of the world's top-four green car technology players by 2020. To achieve the goal, targets of green car deployment was proposed; 1 million electric vehicles, 405 thousand hybrid vehicles, and 1.8 million clean diesel vehicles by 2020
New Comprehensive Plan on Fine Dust	2016-	Ministry of Environment	BEVs	FCEVs	MOE [32]	p19: provides targets for both BEVs and FCEVs (longer term)
Hydrogen Economy Roadmap	2019-	MOTIE		FCEVs	*Korean Hydrogen Economy Roadmap* [33]	2040 goals for FCEVs

Table SI14
UK's strategic orientation policies

Policy name	Period	Government body	Primary technology	Secondary technology	Reference	Evidence from the document
Power Future Vehicles Strategy	2002-2011	Department of Transport	No clear strategy		DfT UK [34]	”Introduction: The strategy is not a technology masterplan, because this is neither possible nor sensible, with many technologies and fuels being actively worked on.[. . .] Although the ultimate low carbon destination looks likely to be fuel cells using renewably-produced hydrogen, the detailed route to that destination will depend on how the many technical issues are resolved. p6: all targets are expressed in technology-neutral terms (in terms of emission levels rather than specifying a technology)”
Making the Connection- The Plug-In Vehicle Infrastructure Strategy	2011	Office for low-emission vehicles (OLEV)	All types (technology neutral)		OLEV [35]	The OLEV 2013 report mentions this 2011 report as the first government strategy report on ultra-low emission vehicles. It pronounces itself for a plurality of technologies with a current-term focus on PHEVs. ”As set out in the UK Automotive Council's technology roadmap, we recognise that in the future there will be a portfolio of low emission technologies for different transport applications – including plug-in vehicles, hydrogen fuel cells, sustainable biofuels and ultra efficient internal combustion engines. [...]But the emergence of plug-in vehicles as a real option for consumers and businesses, and as an opportunity for the associated supply chain, has begun, and we are taking practical steps to put the UK at the forefront of this global market.”
Driving the Future Today	2013-	Office for low-emission vehicles (OLEV)	All types (technology neutral)		OLEV [36]	”It is not Government's role to identify and support specific technologies at this early stage. Ultimately, the mass market transition to ULEVs will happen through industry developing and bringing products to market and consumers deciding which products they wish to buy. The emerging consensus in the automotive industry is that a portfolio of solutions will be required to decarbonise road transport. [...] The Government has consistently supported the development of hydrogen fuel cell vehicles alongside the roll-out of plug-in vehicles as part of its technologically neutral approach. That is why we are actively working with companies in the ground-breaking UKH2 Mobility project to develop a business case for the roll-out of hydrogen fuel cell electric vehicles (and the associated hydrogen refuelling infrastructure) in the UK from 2015. [....] p87: Technological neutrality – The Government will not seek to 'pick winners' in terms of emerging technologies at this early stage. Instead we will support activities that are backed by industry consensus, allowing the market to ultimately determine which technologies win through. We will generally specify the bulk of our policies in output rather than technology terms.”
Road to Zero strategy	2018-	Department of Transport	BEVs, PHEVs	FCEVs	DfT UK [37]	”We remain technology neutral, but recognise that the vast majority of vehicle manufacturer plans include plug-in battery electric powertrains. This section sets out government's role in the build-up of the supporting these electric vehicles' (EV) charging infrastructure for passenger cars and small vans and how we will manage the wider impacts to our power system. [...] Our vision is to have one of the best EV infrastructure networks in the world. [...] The global market for hydrogen fuel cell electric vehicles is at an earlier stage of development than for plug-in electric vehicles. But there is also potential to use hydrogen in applications beyond transport.” ⇒ despite a rhetoric of tech neutrality, this roadmap indicates a clear road of travel with immediate deployment of EVs and hedging uncertainty around the longer-term development of FCEVs.

Table SI15
USA's strategic orientation policies

Policy name	Period	Government body	Primary technology	Secondary technology	Reference	Evidence from the document
Alternative Motor Fuels Act	1988-	Congress	Biofuels		Pub.L. 100-494	p2: the purpose of this Act is to encourage 1) the development and widespread use of methanol, ethanol and natural gas as transportation fuels by consumers, and 2) the production of methanol, ethanol and natural gas powered motor vehicles
President's National Energy Policy	2001		No clear strategy		*National Energy Policy* [38]	Alternative fuel vehicles (AFVs) can run on methanol, ethanol, compressed natural gas, liquefied natural gas, propane, hydrogen, electricity, biodiesel, and natural gas.
State of the Union	2003	President	FCEVs		President G.W. Bush [39]	Our third goal is to promote energy independence for our country, while dramatically improving the environment. [...] Tonight I'm proposing $1.2 billion in research funding so that America can lead the world in developing clean, hydrogen-powered automobiles. [...] A single chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car – producing only water, not exhaust fumes. With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom, so that the first car driven by a child born today could be powered by hydrogen, and pollution-free. Join me in this important innovation to make our air significantly cleaner, and our country much less dependent on foreign sources of energy.
Title 8 of the Energy Policy Act of 2005 (also known as the Spark Matsunaga Hydrogen Act)	2005	Congress	FCEVs		Pub.L. 102-486	The purposes of this title are— (1) to enable and promote comprehensive development, demonstration, and commercialization of hydrogen and fuel cell technology in partnership with industry; (2) to make critical public investments in building strong links to private industry, institutions of higher education, National Laboratories, and research institutions to expand innovation and industrial growth; (3) to build a mature hydrogen economy that creates fuel diversity in the massive transportation sector of the United States;
Hydrogen Posture Plan	2006	DOE, DOT	FCEVs		DOE [40]	The goal is "technology readiness" of hydrogen production, delivery, storage, and fuel cell technologies, to enable the automobile and energy companies to opt for commercial availability of fuel cell vehicles and hydrogen fuel infrastructure by 2020.
American Recovery and Reinvestment Act	2009	Congress	PHEVs, BEVs	FCEVs, biofuels	Pub.L.111-5	Fuel cells and biofuels are each mentioned in one section relating to vehicles, whereas batteries are mentioned in six different sections relating to vehicles.
					White House [41]	Modernizing Transportation, including Advanced Vehicle Technology and High-Speed Rail "In 2009, the U.S. had only two factories manufacturing advanced vehicle batteries that power electric vehicles and produced less than two percent of the world's advanced vehicle batteries. The Recovery Act is investing over $2 billion in advanced battery and electric drive component manufacturing. By 2012, 30 factories with the capacity to produce an estimated 20 percent of the world's advanced vehicle batteries will exist in the U.S.2 At full scale, they will produce enough batteries and components to support 500,000 plug-in and hybrid electric vehicles."
DOE Fuel Cell Program	2011-2020	DOE		FCEVs	DOE [42]	"Reducing emphasis on a single "technology-readiness" milestone for light-duty vehicles and pursuing a vision of technology advancement that involves continuous improvement in many technology areas and for many applications, with new applications reaching technology readiness at different times. Technology and market success in several applications can enable a domestic supply base and pave the way for fuel cell electric vehicles in the longer term" ⇒ This is a recognition by the DOE's fuel cell and hydrogen program that FCEVs are no longer the focus for lightweight vehicles. Instead, a multi-sectoral approach is taken, and the option is left open that FCEVs may become a long-term option for lightweight vehicles.
State of the Union	2011	President	PHEVs, BEVs		President B. Obama [43]	In his 2011 State of the Union address, President Obama called for putting one million electric vehicles on the road by 2015 – affirming and highlighting a goal aimed at building U.S. leadership in technologies that reduce our dependence on oil.1 Electric vehicles ("EVs") – a term that includes plug-in hybrids, extended range electric vehicles and all-electric vehicles – represent a key pathway for reducing petroleum dependence, enhancing environmental stewardship and promoting transportation sustainability, while creating high quality jobs and economic growth.
EV Everywhere Grand Challenge	2012	President; DOE-wide	PHEVs, BEVs		DOE [44]	"Recognizing that vehicle electrification is an essential part of our country's "all-of-the above" energy strategy, President Obama issued the EV Everywhere Grand Challenge to the nation in March 2012 with the bold goal to be the first nation in the world to produce plug-in electric vehicles that are as affordable for the average American family as today's gasoline-powered vehicles within the next 10 years."

Continued on next page

Table SI15 – continued from previous page

Policy name	Period	Government body	Primary technology	Secondary technology	Reference	Evidence from the document
No large-scale policy targeting a particular technology or nation-wide target. State-level market-pull initiatives.	2016-2020		no clear strategy			

D.2 RD&D Funding Data Sources

Table SI16
RD&D Funding Data Sources by Year

Country	Period	Technology	Source
France	1995-2001	Hydrogen fuel cells	OECD [45]
	2001-2020	Both technologies	International Energy Agency [46]
Korea	1995-2002	Hydrogen fuel cells	OECD [45]
	2004-2020	Both technologies	International Energy Agency [46]
Japan	1995-2001	Hydrogen fuel cells	Maeda [47]
	2002-2006	Hydrogen fuel cells	Ishitani & Baba [22]
	1992-2002	Other energy storage	Åhman [19]
	2004-2020	Both technologies	International Energy Agency [46]
USA/DOE	1995-2003	Both technologies	Gallagher & Anadon [48]
	2004-2015	Both technologies	International Energy Agency [46]
	2016-2020	Both technologies	Gallagher & Anadon [48]
China	1995-2000	Both technologies	Zhang *et al.* [49]

Note: The main data is from the IEA Energy Technology RD&D Budgets Database, 1974-2022 (2022 edition). The variables selected are Government R&D and Government Demonstration, where for fuel cell hydrogen, we select Group 5 (Hydrogen and Fuel Cells) and for other storage, we select Group 6 (Other Power and Storage Technologies) and subgroup '1311 Vehicle batteries/storage technologies'. These technology categories were the closest match to the other sources of public RD&D data used to cover the time period of interest.

D.3 Firm-Level Regressions

Table SI17
Exposure to National Orientations and Battery/FC Focus

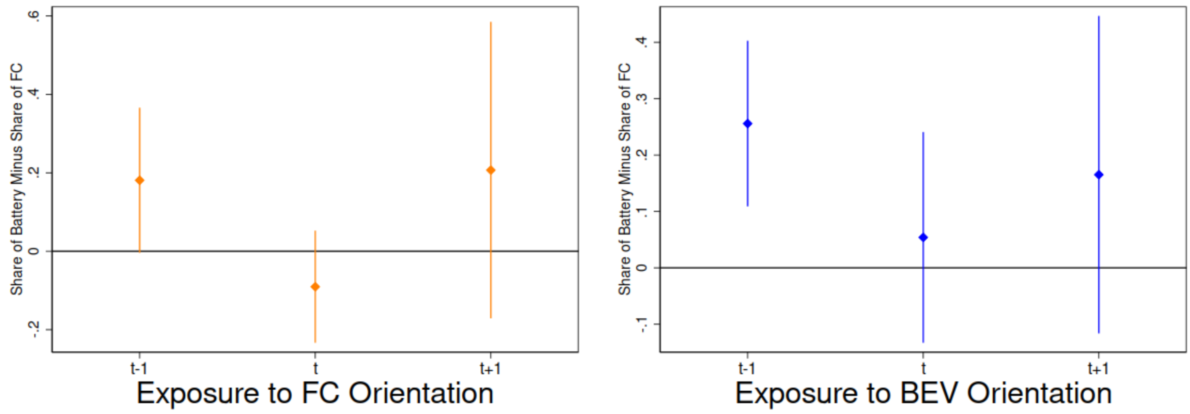
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
FC Orientation t-1	0.05	0.01	0.11	0.12					0.23**	0.18*	0.30*	0.27*
	(0.07)	(0.07)	(0.15)	(0.11)					(0.10)	(0.09)	(0.18)	(0.14)
FC Orientation	-0.11**	-0.12**	-0.28**	-0.29**					-0.09	-0.09	-0.19	-0.18
	(0.05)	(0.05)	(0.13)	(0.14)					(0.07)	(0.07)	(0.14)	(0.14)
FC Orientation t+1	-0.22**	-0.22**	0.24*	0.17					0.11	0.21	0.10	0.21
	(0.09)	(0.10)	(0.14)	(0.13)					(0.17)	(0.19)	(0.18)	(0.21)
BEV Orientation t-1					0.20***	0.15***	0.14	0.06	0.32***	0.26***	0.30	0.25
					(0.05)	(0.05)	(0.20)	(0.14)	(0.07)	(0.07)	(0.25)	(0.16)
BEV Orientation					0.07	0.10	0.30	0.28	0.03	0.05	0.22	0.21
					(0.07)	(0.06)	(0.18)	(0.18)	(0.10)	(0.09)	(0.20)	(0.20)
BEV Orientation t+1					0.10	0.07	-0.13	-0.10	0.11	0.17	-0.09	0.07
					(0.06)	(0.07)	(0.18)	(0.18)	(0.15)	(0.14)	(0.25)	(0.28)
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	0.05	0.49	0.18	0.55	0.18	0.54	0.20	0.56	0.20	0.55	0.21	0.57
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. * $p<0.10$, ** $p<0.05$, *** $p<0.01$

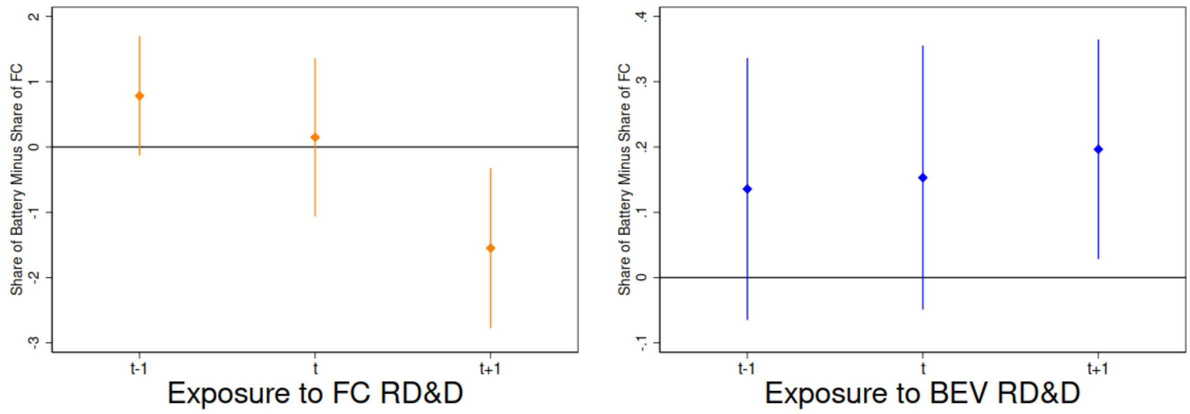
Table SI18
Exposure to RD&D Funding and Battery/FC Focus

	(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					0.44	0.73*	-0.25	0.18
	(0.51)	(0.46)	(0.58)	(0.66)					(0.48)	(0.40)	(0.59)	(0.63)
FC R&D	-0.08	-0.43	-0.09	-0.66					-0.27	-0.51	-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					-1.43**	-1.73***	-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	-0.05	-0.17
					(0.08)	(0.10)	(0.10)	(0.12)	(0.10)	(0.10)	(0.13)	(0.15)
BEV R&D					0.20***	0.19**	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					0.18*	0.09	0.06	-0.24	0.16*	0.06	0.04	-0.13
					(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	0.48	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. * $p<0.10$, ** $p<0.05$, *** $p<0.01$



(a) Coefficients for Column 10 in Table SI17



(b) Coefficients for Column 10 in Table SI18

Figure SI21
Fuel Cells vs. BEV Policies

Note: Figure SI21a plots the coefficients from regression (10) in Table SI17, while Figure SI21b plots the coefficients from regression (10) in Table SI18.

E Other Additional Information

E.1 BEVs and FCEVs: A Overview of Relative Advantages and Disadvantages

Introduction

The comparison between fuel cell (FCEVs) and battery electric vehicles (BEVs) is complex. Our main text, due to space constraints, mentioned a few key points. We noted that there was and still isn't no obvious first best between BEVs nor FCEVs. Both present significant pros and cons when considering the transition away from traditional ICE cars, and opinions varied and still vary today regarding the prospect for each technology of overcoming key obstacles. Here, we dive deeper into perceptions of their relative strengths and weaknesses.

The determination of which technology is "better" will vary based on the importance given to different criteria. This can not only change over time but also across different stakeholders. The assessment of specific criteria will also shift when considering short-term versus long-term perspectives, because technological costs may decrease and performance improve. Finally, the level of market penetration will also greatly affect the comparison, in particular because some technological constraints may be less binding at low penetration.

Keeping the Status Quo in Mind. It's crucial to frame the comparison of BEVs and FCEVs in the context of their intended replacement for ICE vehicles which have been extensively produced and used for decades. ICE vehicles typically offer low upfront costs, widespread and affordable fueling options, and long travel ranges, making them convenient for users. This convenience comes at the cost of complexity, with ICE cars having numerous parts, requiring regular maintenance and repair and having lower energy efficiency compared to vehicles powered by electric motors. However, assuming these support services are readily available and affordable, the operation of ICE cars remains straightforward and dependable for most consumers.

Criterion 1: Recharging/Refueling Speed and Range.

BEVs and FCEVs offer different experiences in terms of how quickly they can be refueled or recharged and the distances they can travel on a single charge or fill-up.

FCEVs have a longer range than BEVs with a single hydrogen fill-up, which is attractive for vehicles like buses and trucks, but also for smaller vehicles with long-distance travel needs. Refueling a FCEV can take about five minutes [50], similar to an ICE car, unlike BEVs which need more time to charge, even with fast chargers. The heavy batteries needed for BEVs to match FCEV ranges can be a drawback, especially for larger vehicles [50]. FCEVs can also handle extreme hot and cold better than BEVs, whose battery performance can drop in such conditions.

Low vs. High Penetration: It's crucial to note that at low penetration levels, BEVs can bypass issues of battery capacity and long charging times. This is because early BEV adopters are often able to charge their vehicles at home overnight and might buy a BEV as a second car alongside their ICE vehicle. Thus, they tend to use the BEV for short trips (after charging it fully overnight) and rely on their ICE car for longer journeys. However, as BEV adoption increases across all income levels, with more households purchasing and using BEVs, the challenges related to battery capacity and charging times become more pronounced and harder to manage [51].

Criterion 2: Charging vs Hydrogen Refueling Infrastructure

The availability and development of infrastructure for charging BEVs and refueling FCEVs significantly impact the practicality and convenience of using these vehicles compared to the well-established fueling infrastructure for ICE cars. FCEV adoption hinges on creating a hydrogen refueling infrastructure, meaning stations must be built to supply hydrogen fuel. BEV adoption, conversely, demands a network of fast-charging stations and a reliable electricity supply.

In a low-adoption scenario, BEVs can sidestep key infrastructure challenges, as early adopters, typically high-income households with private residences, can charge their vehicles overnight. Furthermore, these early adopters often buy a BEV as a secondary vehicle alongside their ICE car, effectively circumventing the major bottlenecks of BEVs: battery range and the density of fast-charging station network.

In a scenario of widespread adoption, there are compelling reasons to believe that addressing upstream infrastructure challenges could be more straightforward for FCEVs than for BEVs.

The transformation required for BEV charging infrastructure at scale is considerably more significant than introducing hydrogen as an additional fuel onto the existing network of petrol stations. In 2010, the EU Coalition Study (involving governments, car makers, utilities, climate research groups, oil and gas companies, and electrolyser companies) estimated that "over the course of the next decades, costs for a hydrogen distribution and retail infrastructure are 5% of the overall cost of FCEVs (1,000-2,000 euros per car) and comparable to rolling out a charging infrastructure for BEVs and PHEVs, excluding potential upgrades in power distribution networks."

Hence, the coalition estimated that the costs would be comparable, but this is not accounting for the costs of upgrading the existing grid to accommodate the additional load that BEVs will create, particularly at peak charging times. This will pose logistical and financial challenges, especially given the existing pressures from variable renewable generation and the electrification of other sectors.

In contrast, hydrogen is less disruptive to the grid [51] and can be transported by retrofitting existing pipelines but also simply by trucks and the infrastructure doesn't need to be as dense since FCEVs have longer range [52]. The primary bottleneck for FCEVs therefore appears to be the cost of hydrogen production rather than its transport and distribution.

It is also worth noting that some countries, like Japan, rely on their own isolated electrical grid to support all energy supply and therefore see in hydrogen a critical option to diversify their energy systems [26].

Criterion 3: Costs.

When comparing the costs associated with BEVs and FCEVs, it's essential to consider both the cost of the battery units and electricity for BEVs, and the cost of the fuel cell units and of hydrogen itself for FCEVs.

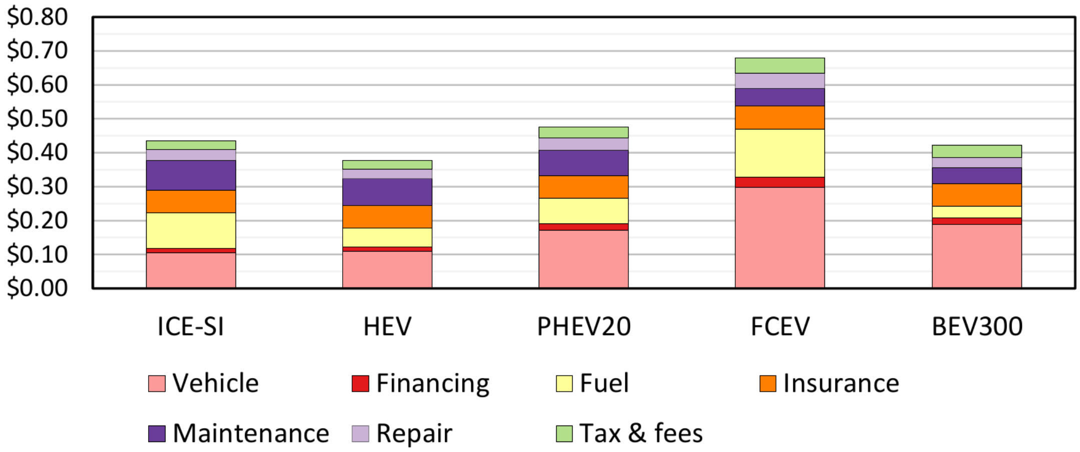
As documented in this main text, both battery and fuel cell costs have seen significant reductions since 1990. The costs of FCEV still remain more expensive than BEVs, but industry experts expect significant scale economies as several steps in the production of fuel cells become automated [53, 54].

While electricity costs can vary greatly depending on location, it has become generally very affordable. On the other hand, hydrogen remain expensive. However both the costs of blue hydrogen (from natural gas reforming with carbon capture) and green hydrogen (from electrolysis of water) are expected to continue falling with continued innovation [55, 56], and economies of scale [57].

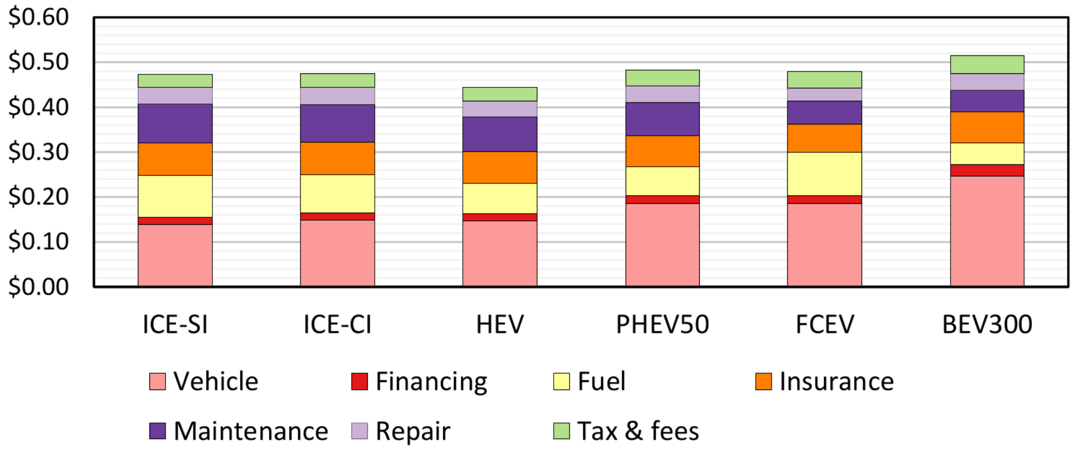
A rigorous cost comparison between BEVs and FCEVs would require assumptions on how vehicles are used, fuel efficiency and frequency of repairs among other things. A recent report from the Argonne laboratory provides useful calculations on the levelized total costs of ownership for different sizes, classes and powertrain technologies [58]. As an illustration, we reproduce on Figure SI22 below three key graphs from this report which illustrate the variation in average per-mile cost of driving across powertrain.

Panel SI22a shows that an FCEV bought in 2019 is still significantly more costly than a BEV with a 300-mile range. However, when comparing cost based on expectations for vehicles available in 2025 (Panel SI22b), the FCEV now becomes slightly less expensive than the BEV and could even reach cost parity with the plug-in hybrid electric. These are on average cost per mile, calculated over a period of 15 years. Panel SI22c presents a similar calculation but over a shorter, 5-year, window. In this case, the FCEV remains more expensive than the plug-in but still slightly cheaper than the BEV. The disparity between 15-year and 5-year calculations underscores the significant impact of hydrogen fuel cost reductions over time.

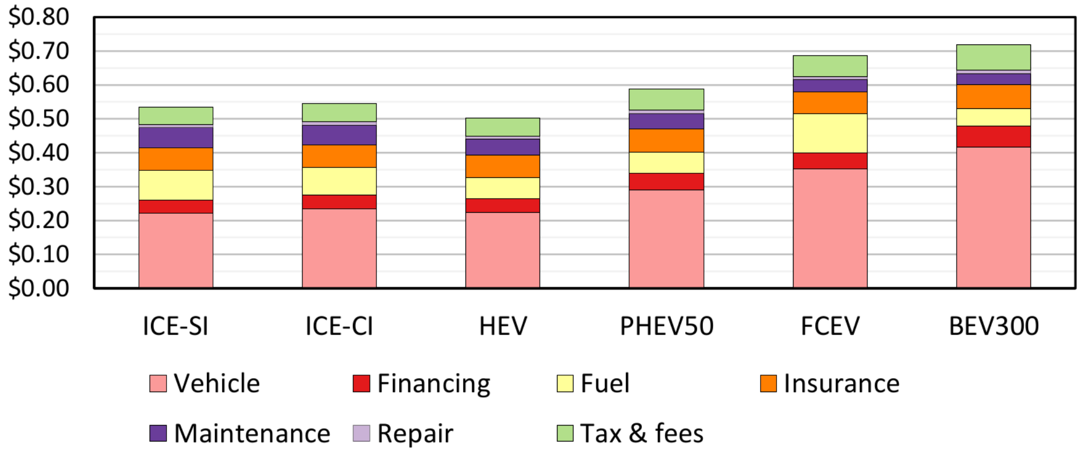
The information presented in this report serves merely as an example of potential cost comparisons between powertrains. It's crucial to note that these calculations are based on a variety of assumptions and future cost projections. Consequently, there is an inherent level of uncertainty not reflected in the accompanying figure.which is not captured on the figure.



(a) Over 15-year for a small SUV sold in 2019



(b) Over 15-year for a small SUV sold in 2025



(c) Over 5-year for a small SUV sold in 2025

Figure SI22

Average Per-Mile Cost of Driving Across Powertrain

Note: Source: [58]. On Figure SI22b and SI22c, the vehicle was modeled to be representative of a vehicle that could be available in 2025. A 15-year or 5-year analysis window was assumed, along with a 1.2% discount rate and a 4.0 interest rate on a 63-month loan. ICE-SI stands for spark-ignition internal combustion engine. ICE-CI for compression-ignition internal combustion engine. HEV for hybrid electric vehicle. PHEV20 and PHEV50 for plug-in hybrid electric vehicle with 20- or 50-mile range respectively. FCEV for fuel cell electric vehicle. BEV300 for battery electric vehicle with 300-mile range. For more details, see [58]

Criterion 4: Critical Minerals.

Critical material constraints can arise for electrolyzers and fuel cells (especially platinum group elements), as well as batteries (especially lithium and cobalt, and to a lesser extent manganese and nickel) [59]. These supply issues and the need for innovation in recycling of critical minerals is thus salient for both technologies.

Criterion 5: Greenhouse Gases Emissions.

Both BEVs and FCEVs have the potential to significantly reduce emissions in road transport [60]. BEVs emissions depend on the electricity's source, with variations in carbon intensity based on location and time. BEVs has the potential to be truly net-zero if it is powered by electricity from grids that use a mix of renewables, nuclear, large-scale storage, and carbon capture for net-zero emissions.

For FCEVs, emissions hinge on the hydrogen production method. It therefore also has the potential to be net-zero, if it sources hydrogen produced from renewable energy via electrolysis or natural gas reforming with carbon capture and storage.

However, determining which path to decarbonization will be more feasible in practice remains complex.

Discussion.

Dominance of FCEVs in the Early 2000s. In 2000, the widespread belief was that FCEVs would become the main option for long-distance vehicles while BEVs were seen as suitable only for short-range, compact cars. This perspective, detailed in our Online Appendix Subsection E.2, can be explained by the fact that BEVs' key bottlenecks (battery range and costs and the need for charging infrastructure) made FCEVs, by far, much closer substitutes to ICE cars.

Shift to BEVs after 2005. The improvements in battery performance and cost made several niche markets viable: luxury segment (e.g., Tesla around 2008) or medium to high-income households with private residences, allowing for home charging and typically buying a BEV as a secondary vehicle, retaining their ICE vehicles for longer trips. Other niche markets included small compact cars for short-distance trips (e.g., Chinese consumers) and hybrid vehicles as a way of improving the carbon efficiency of ICE cars. For these niche markets, the limitations of battery range and the scarcity of charging stations were not critical.

FCEVs as a long-term option? The consensus on the future of FCEVs is not unanimous. While some automakers have steered away from FCEVs, many in the industry maintain investments in both BEVs and FCEVs. The debate hinges on expectations regarding battery improvements (range, charging speed and charging infrastructure expansion), the cost of hydrogen, and the degree of commitment to net-zero transportation.

BEVs face inherent limitations in battery size and charging time, even with innovations like solid-state batteries, which promises 80% recharge in 15 minutes and ranges over 800 kilometers. FCEVs will always offer quicker refueling and longer ranges, making them a closer alternative to ICE cars from a user experience standpoint. A key uncertainty, however, is whether green hydrogen becomes sufficiently affordable.

The degree of global commitment to net-zero transportation is also a critical uncertainty. Achieving 100% green hydrogen may be seen by some actors as more straightforward than fully decarbonizing electricity. On the other hand, with an 80% decarbonization goal, relying on plug-in hybrids BEVs, that is using the electricity from the battery but still gasoline for beyond-range needs, could be a viable strategy.

E.2 Evidence about the Perception of FCEVs vs BEVs in 2000-2008

This subsection provides detailed evidence to substantiate the claim that around 2005 FCEVs were widely seen as the likely dominant technology in the long-range vehicle market, with BEVs expected to cater primarily to short-range compact cars.

Views as reported in a 2000 report by the Swedish government's Transport Research Board.

The 2000 report from the Swedish government, representing a small economy in the global automotive market, offers valuable insights into the industry trends of that time. Unlike governments in larger markets such as the USA, which may actively influence the direction of technological change, Sweden's position required it to be a more passive observer. This context makes the report a reliable source for understanding industry perceptions, as it is less likely to be coloured by ambitions to steer technological change and more reflective of the actual industry dynamics and expectations during that period. Below are a series of citations from the report:

- "In the last years of the decade the focus shifted and "fuel cell" became the buzz-word in the auto industry. Today all major auto manufacturers are investing billions of their own money in fuel cell vehicle R&D. The oil industry is supporting with the investigations into new fuels like methanol and hydrogen and reading press-releases would make you expect to find the new fuel cell vehicles in the shop already in two or three years time!"
- "Many experts view BEVs as a transitional technology as hybrids or fuel cells develop, with applications for BEVs as small city cars or specialty, short-range vehicles."
- "The only major manufacturer to publicly state that it does not see a potential for fuel cell vehicles is BMW."
- "Demonstrations of fuel cell vehicles will be common within a few years. [...] Developments in future advanced fuel cell types and carbon-based hydrogen storage is likely to advance quickly."

This 2000 Swedish report vividly captures the automotive industry's trend towards fuel cell technology at that time. It reflects a widespread industry belief in fuel cells as the future of automotive innovation, contrasting with a more limited view of BEVs as transitional or niche solutions.

Views from the engineering peer-reviewed literature.

The engineering systems literature between the years 2000 and 2007 generally gives the impression that FCEVs were the main contenders against ICEs. A 2003 MIT report on the prospects for new propulsion technologies focuses on the comparison between FCEVs and ICEs, noting that in practice batteries' range is expected to remain insufficient [61].
It is not uncommon in that period for papers to start with statements such as "Fuel cells are widely expected to replace internal combustion engines in vehicles" [62]. A *Scientific American* article from 2005 similarly casts FCEVs as the zero-carbon car of the future, while putting the spotlight on the many technical and market hurdles on the way to full commercialization [63].
In 2008, a review article by Sperling and Gordon in the *Annual Review of Environment and Resources*, while noting progress in the area of batteries, nonetheless labelled fuel cells as "the

Holy Grail" of clean transport. They further noted the following:

- "On the basis of statements by these companies [Daimler, GM, Honda, Nissan, and Toyota], personal visits by the authors to their facilities, and press reports of the number of engineers employed on fuel cell research and design, it appears that each of the five companies have invested at least $100 million per year in the technology since about 2000 (which is much more than they were spending on any other alternative fuel option and much more than governments were spending)."
- "Through it all, hydrogen fuel cell vehicles retain one important edge over battery electric vehicles and plug-in hybrids: They are strongly preferred by many of the largest automotive companies. "

Views from industry players.

The 2005 KPMG Annual Global Automotive Executive Survey asked the following question: "Of the following automotive product innovations, which do you believe will be the three most important to the industry over the next five years?". The possible answers included fuel cell technology but not battery electric vehicles (indicating the KPMG did not then consider BEVs as a serious product innovation). The reported results show that between 2001 and 2005, around 50 to 60% of executives rated FC technology as amongst the three most important developments (depending on the year), just behind safety innovations.
Toyota's 2006 corporate report labels fuel cells the "ultimate eco car" and displays fuel cell hydrogen cars as the future solution, with hybrids as the interim solution. A new focus on advanced batteries is first mentioned in the 2008 sustainability report and the 2009 annual report. On a different continent, PSA's 2006 corporate report states "Hydrogen fuel cells offer a longer-term solution for the environment."

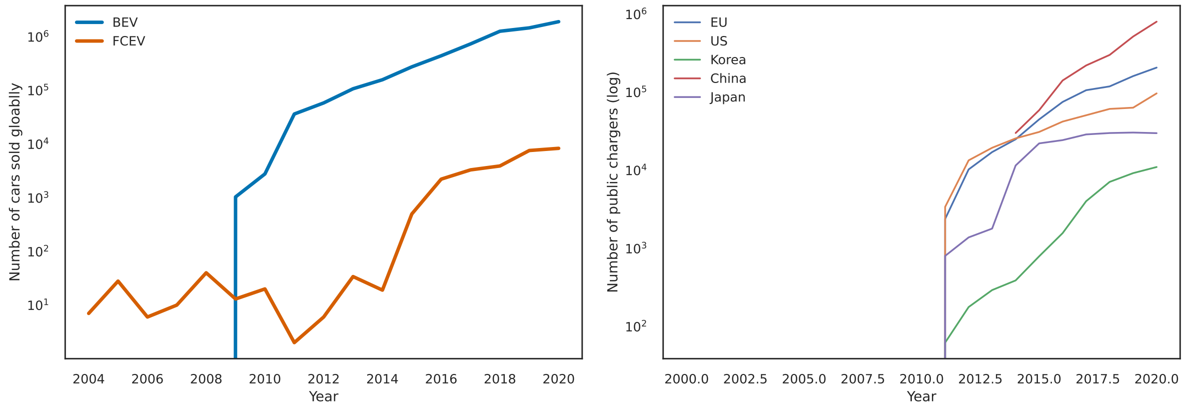
Conclusion

The evidence from varied sources around the early to mid-2000s clearly aligns with the claim that FCEVs were anticipated to be the dominant technology for long-range vehicles, with BEVs envisaged more for short-range and compact car applications. This period saw significant interest and investment in FCEV technology, reflecting a broader industry consensus during that time.

E.3 FC Prices and EV sales

Table SI19
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 SI23
EV sales and charger availability start in earnest after 2010

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