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

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March 2, 2024

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Abstract

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

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

Significance Statement

The transition to low-carbon technologies is an urgent global challenge. While existing recommendations focus on expediting clean technology cost reductions and policy-induced adoption, our research offers a new, complementary perspective. We explain when these transitions can be viewed as global coordination games. Turning to the car industry, we highlight that the choice it had to make between FCEVs and BEVs is an example of such a coordination game. We document an unexpected shift in the industry from an initial focus on FCEVs to BEVs, a change that coincided with a wave of exogenous battery advancements in electronics. Our findings underscore the often-ignored role of cross-sectoral spillovers and provide a rationale for globally coordinated industrial policies.

Introduction

Addressing climate change requires decarbonizing the transportation sector. Currently, Battery Electric Vehicles (BEVs) are in the spotlight, with major car manufacturers setting bold BEV goals, governments investing in charging stations and setting phase-out objectives for Internal Combustion Engines (ICE). However, BEVs aren't the only option. Fuel Cell Electric Vehicles (FCEVs) have been regarded as another promising choice, and for a long time, there was no clear favorite between the two. What then made the industry lean more towards BEVs?[1]

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

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

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

While there is growing research on the shift to BEVs[11–14], this paper is the first to quantitatively study firms' choice to innovate on FCEVs versus BEVs and to provide an explanation for the industry's eventual shift to BEVs. In doing so, the paper sheds new light on the critical question of how to effectively direct technological change toward cleaner technologies. A clear theoretical paradigm has emerged to answer this question[15–20], buttressed by numerous case studies of the growth of the solar and wind energy sectors[21–23]. In contrast to these well-studied 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,

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

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].

1 Technological choice as a global coordination game

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

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

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

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

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

When can several technologies co-exist? Figure 1c brings together the two dimensions discussed above to make predictions about the scale of coordination needed to enable investments in a radically new technology. When there's no technological interdependence, firms have the flexibility to explore any technological path. But in the presence of complementarities, coordination becomes essential for a clean option to emerge. Coordination here simply means that firms end up choosing the same technology, 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.

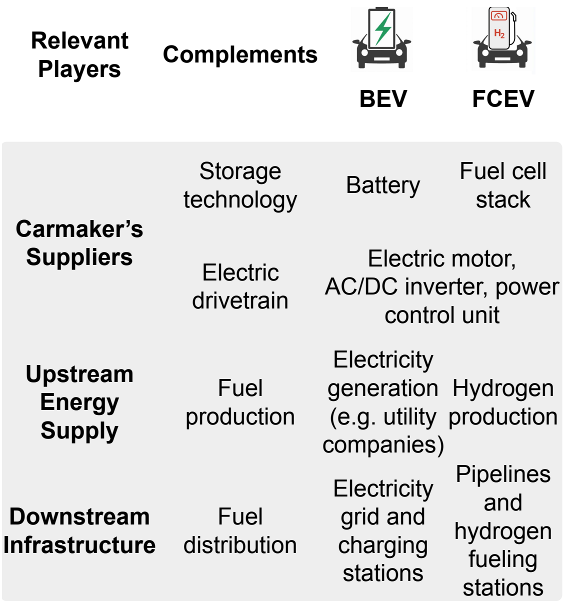
However, if market integration is high, as we argue it is in the car industry, players must converge on one technology. History offers numerous examples of industries faced with multiple technological options that were incompatible due to their lack of modularity, leading to the dominance of one option[35,36]. 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 Online Appendix Subsection E.2).[3]

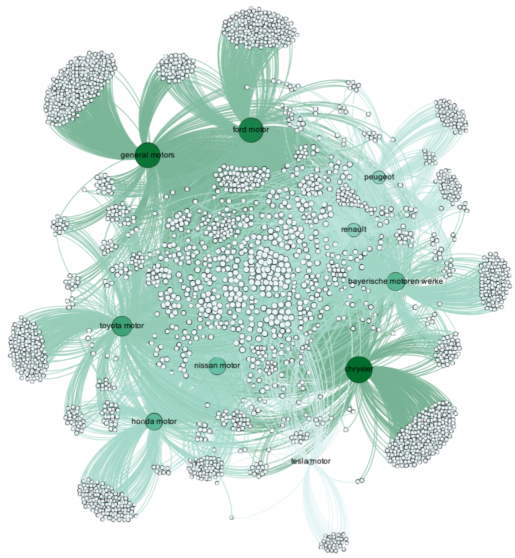
Tesla and Hybrid Cars Viewing the shift to clean cars as a global coordination game also helps explain two notable success stories: the development of hybrid vehicles like the Prius and Tesla's pioneering role in the Electric Vehicles (EVs) market. Hybrid vehicles offered a strategy to radically reduce 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.

[3]The challenges in upgrading electricity grids for fast-charging stations do not necessarily look easier than 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 Section E.1.

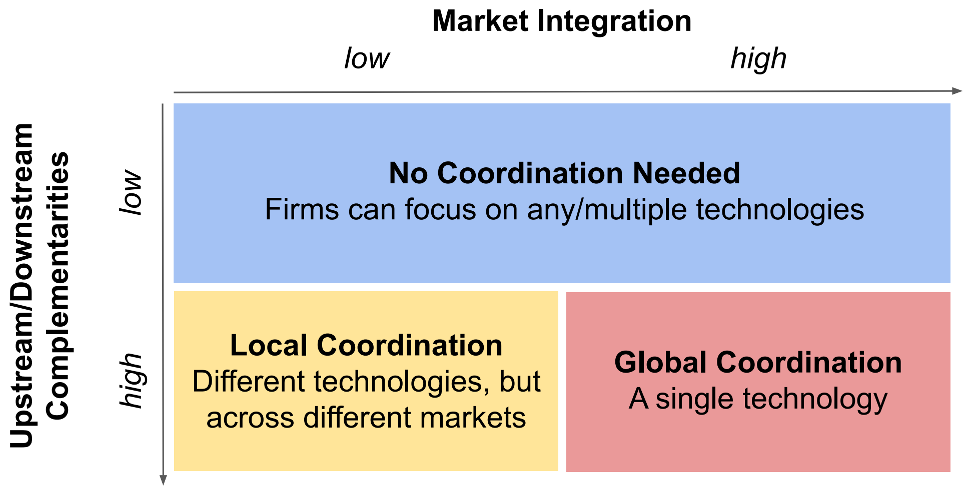
[4]The impact of hybrid technology on BEV adoption is ambiguous, given the different battery types used and the fact that improvements in regenerative braking and electric motors could benefit both BEVs and FCEVs.



(a) Complementarities in Technological Components



(b) A Tightly Integrated Network of Producers and Suppliers



(c) Industry Characteristics and Need for Coordination.

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

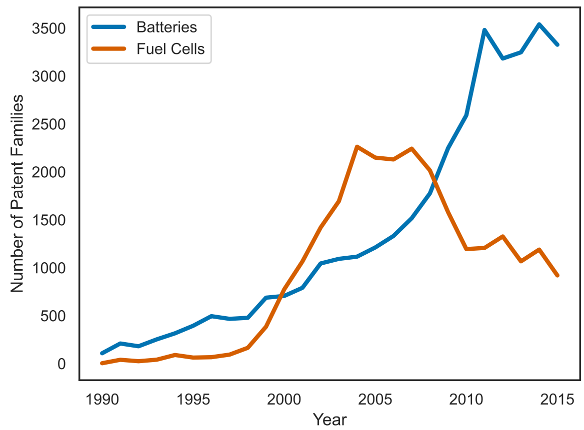
Figure 1
Clean Car Development as a Global Coordination Game

2 FCs patenting declined as battery patenting soared.

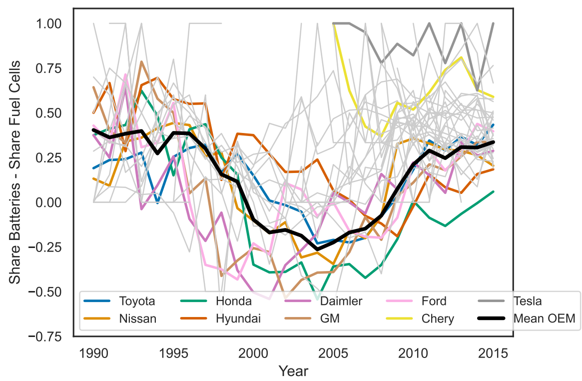
Our analysis of carmakers' innovation strategies shows that since 1990, patents for clean car technologies have surged, overtaking those for ICEs by 2008 (Supplementary Figure C.1). Yet, a deeper look reveals contrasting trends between FC and battery patenting (Figure 2a).

In the late 1990s, carmakers favored FCs, leading to a swift rise in FC patents until 2004. However, by 2007, FCs experienced a stark "reversal fortune": FC patenting stagnated and sharply declined. Concurrently, battery patenting accelerated. These shifts align with US media's 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 FCs and biofuels and reverting to BEVs by 2007[12]. This reversal of fortune occurred alongside sustained growth in electric vehicle (EV) patents (Supplementary Figure C.2), emphasizing electric propulsion elements like e-motors and regenerative braking, relevant to both BEVs or FCEVs. While hybrid vehicle patents also increased significantly, they have plateaued since 2008. On the other hand, patents on hydrogen production and distribution, a critical complement to fuel cells, remained sparse.

Remarkably, carmakers' shift from FCs to batteries is globally synchronized: nearly all major carmakers transitioned similarly, first focusing on FC and later on batteries (Figure 2b). While some initiated this change earlier,[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.

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

3 From a fragmented FC policy landscape to a global 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 FCs from the late 1990s until 2008 (Figure 3b). It then declined, settling at roughly half of its peak

[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.

value. Conversely, funding for electric storage remained flat until 2008, after which it surged in most countries, notably China and the USA.[6]

We then compile and code data on policymakers' *strategic orientation*, frequently outlined in official documents like roadmaps or strategic plans (See Online Appendix 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 FC 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 FC.

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

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

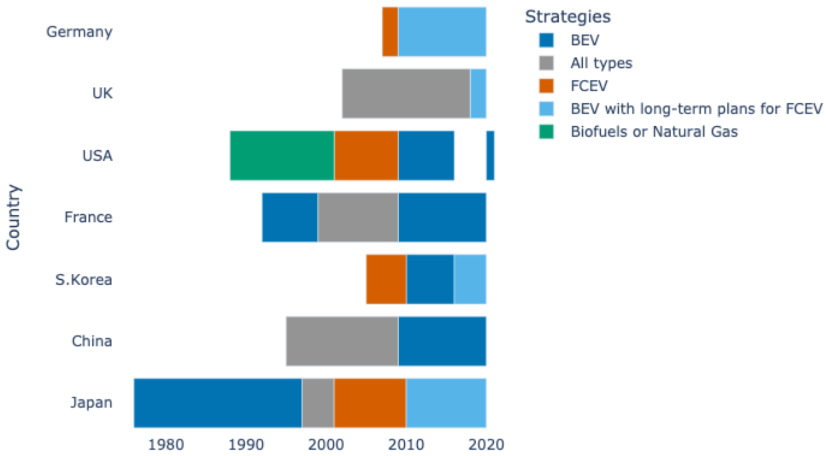
[7]The preference for BEVs now and FCEVs later possibly reflects strategic trade-offs between immediate emission reductions and future technological viability. See Section E.1 for more details.

[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.

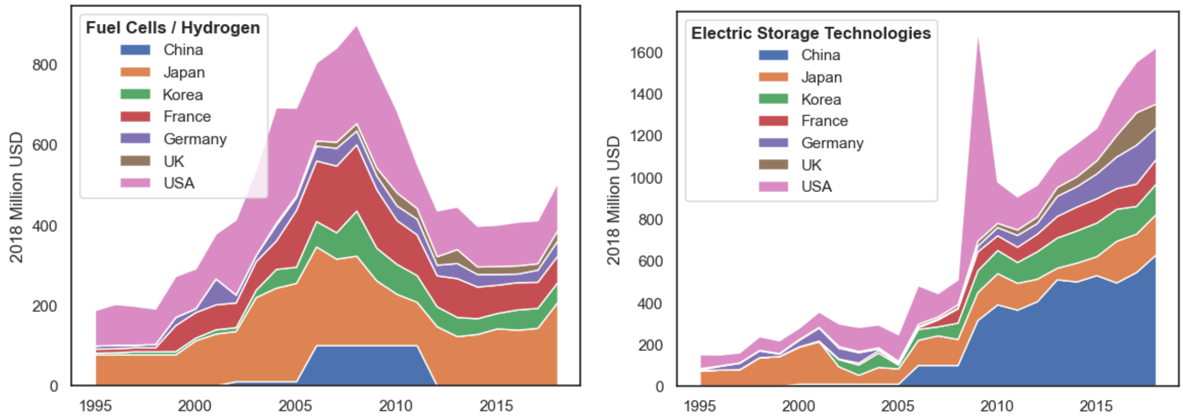
[9]FC orientation surged in the 2000s, due to policies in the US, Japan, and Korea.

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

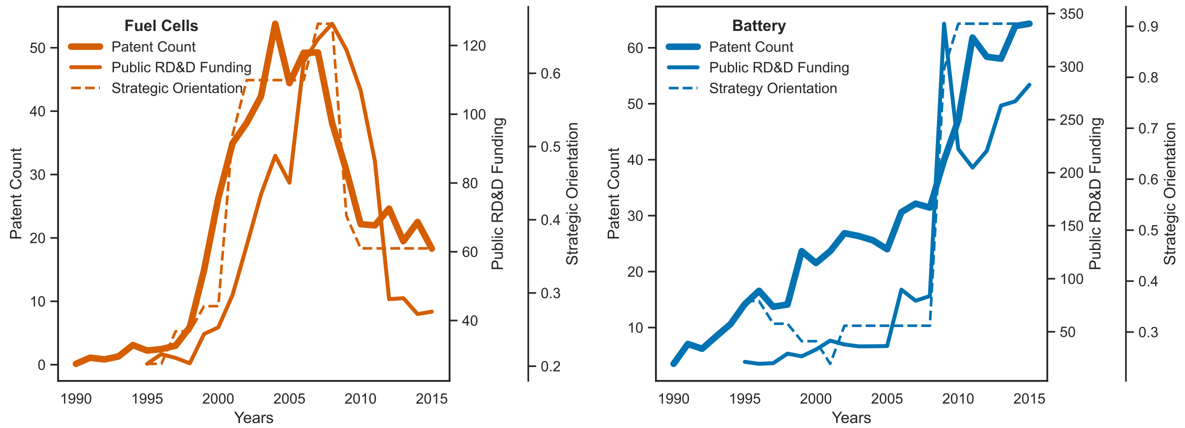
[10]It is possible that the policy shifts induced more battery innovation, however our approach can not say much about this given the possibility for omitted variable bias.



(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

Note: Figure 3a and 3b display the history of strategic orientations and public RD&D funding related to clean vehicles by country over time. The 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.

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

We now turn to the possibility that exogenous innovation spillovers coordinated actors. We extend our dataset to include clean car patents across all economic sectors. We start by examining patents' backward citations to assess the importance of cross-sectoral spillovers. They reveal that carmakers' battery patents predominantly draw upon the knowledge pool outside the industry rather than within (Figure C.6).

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

The story for FCs differs considerably. Here, the Motor Vehicle industry takes center stage, accounting for nearly 35% of all FC patents circa 2005, just before the reversal. Other sectors play a more minor role, largely following carmakers' boom-and-bust cycle. Particularly striking is the limited innovation in sectors where FCs and hydrogen exhibit significant potential, such as maritime and air transport and machinery. The implication is that the knowledge spillovers from other sectors flowing to carmakers were larger for batteries than fuel cells, as shown in Figure C.7, which plots a measure of *expected* spillovers following Acemoglu *et al.* [9].[11]

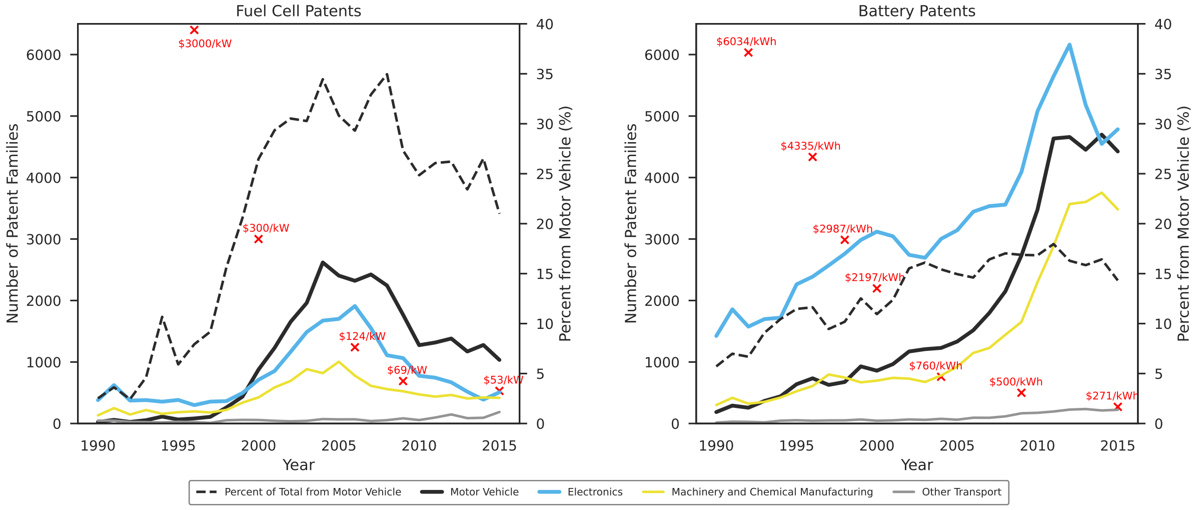
Finally, we examine innovation trends among carmakers' "active" suppliers—those with a recorded supply link to any carmaker in year t. Suppliers are pivotal, not just as input providers, but as conduits for cross-sectoral technological spillovers that can eventually benefit a particular technological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

This is evidence that cross-sectoral spillovers favoring batteries occurred not just through diffuse knowledge spillovers but also through carmakers' rewiring to battery-competent suppliers from outside the automotive industry.[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

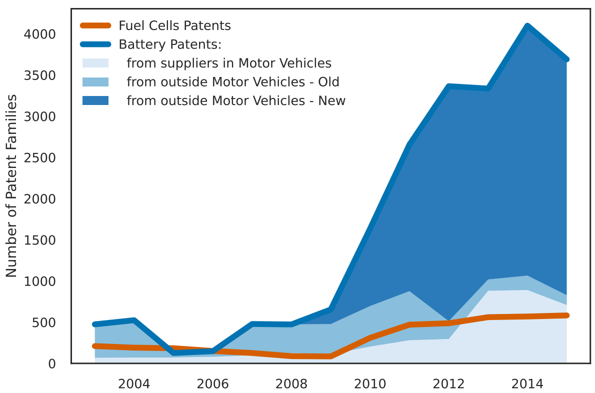
[11] Unlike the raw citation counts of Figure C.6, this measure removes the influence of carmakers' change in patenting and isolate the role of the *availability* of relevant non-carmaker patents. See Section C.3 for details.

[12] In 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.

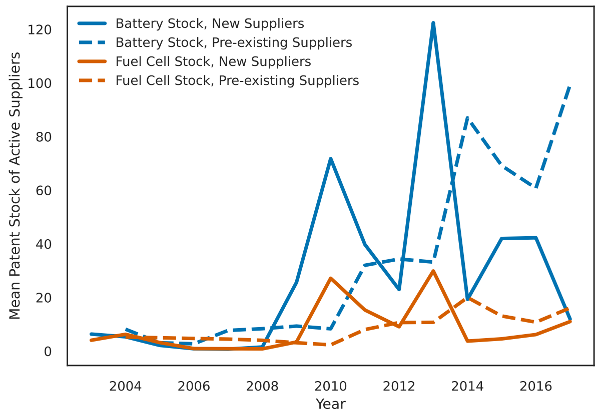
not align with FCs.



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



(b) Patent Counts of Active Suppliers



(c) Patent Stocks of Active Suppliers

Figure 4

Cross-sectoral Spillovers and Greening of the Supply Chain

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

Discussion

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

Our data reveal that carmakers move synchronously rather than pursue distinct technological innovation trajectories in regional markets. Moreover, only when policies globally align to favor BEVs do trailing carmakers and traditional suppliers intensify their efforts toward clean cars. Most critically, car sales and investment in public infrastructure do not start until after the technological uncertainty is resolved (See Figure E.2). 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 FCs to gain traction can be attributed to several factors: inconsistent policies across markets, inadequate sectoral coordination with upstream hydrogen supply, and an absence of collaboration with sectors that could have concurrently advanced fuel cells, generating broader knowledge spillovers.

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

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

But being market-ready doesn't necessarily mean the technology is "best" from a whole-system, long-term perspective,[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].

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

Methods

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

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

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

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

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

We aggregate patent applications at the level of DOCDB patent families, which group patents covering the same technical content and, thus, the same invention. This prevents double-counting inventions.[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 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

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

suppliers; "Electronics" combines NAICS 334 ("Computer and Electronic Product Manufacturing") and NAICS 335 ("Electrical Equipment, Appliance, and Component Manufacturing category"); "Machinery and Chemical Manufacturing" (NAICS 333 and 325); "Education and R&D" (NAICS 611 and 541); "Other Transport" (NAICS 336 except Motor Vehicle).

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

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

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

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

For both RD&D funding and strategic orientations, we calculate a firm's exposure using a weighted average of national policies. The weighting is determined by the firm's 2004 sales share in each country.[15].

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

Data Availability

Certain data in this study come from custom datasets purchased from Marklines, Factset Revere, PATSTAT, and Orbis IP. Due to licensing terms, we are precluded from publicly sharing data related to individual observations. However, aggregate counts derived from this data, as showcased in 2, 3 and 4 will be accessible. Data on public RD&D support is freely available via the International Energy Agency[54]. We compiled additional observations, which we will make available. Country-year data on strategic orientation will be made available.

Code Availability

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

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

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Acknowledgement

We acknowledge the following funding sources: the AXA Research Fund, the LSE Grantham Research Institute on Climate Change and the Environment, and the ESRC Centre for Climate Change Economics and Policy (CCCEP) (ref.ES/R009708/1), the Alfred P. Sloan Foundation through grant G-2019-12323 as well as the LSE Research Support Fund, and LSE STICERD grant. We are grateful to Joëlle Noailly for their helpful comments, as well as the participants of the NBER Economics of Innovation in the Energy Sector Workshop, the GRI Workshop, the Mercator Institute Seminar, and the PSE Annual Conference on Global Issues, where this paper was presented and discussed.

Competing Interest Declaration

The authors declare no competing interests.

Supporting Online Information

Supplementary Information is available for this paper.