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

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Abstract

Significant progress reconciling economic activities with environmental goals requires radical and rapid technological change in multiple sectors. Here, we study the case of the automotive industry's transition to electric vehicles. We argue that technological change in this industry poses a global and multi-sectoral coordination challenge due to technological complementarities and the global organization of its markets and supply chains. We show that while the industry initially focused on fuel cell technologies, around 2008, the technological paradigm shifted to battery electric vehicles. We find that national-level policies had a limited ability to coordinate global players around a type of clean car technology. Instead, innovation spillovers from outside the automotive sector played a critical role in driving the industry's shift to battery electric vehicles. We conclude with implications for accelerating low-carbon technological change in other global sectors and the renewed push to develop hydrogen technologies.

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

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Introduction

Addressing climate change necessitates the decarbonization of the transportation sector. At present, the predominant focus is on Battery Electric Vehicles (BEVs). Many leading automobile manufacturers have set ambitious targets for BEV production, and governments are investing in charging infrastructures. However, BEVs aren't the sole alternative. Fuel Cell Electric Vehicles (FCEVs) have also been regarded as a viable option. For an extended period, there was no definitive preference between the two. What then led the industry to gravitate towards BEVs?

The answer to this question is important for green innovation policy for three main reasons. First, this question leads us to focus on coordination challenges in transitioning to a new technology in a concrete empirical setting. This is noteworthy because the presence of coordination externalities is one of the main justifications given for innovation and industrial policies that aim to shape and grow new markets [1–3]. Yet, there is little evidence of how coordination challenges affect the performance of green innovation policies in practice. Second, coordination challenges can lead to protracted periods of technological uncertainty[4], substantially slowing down the transition to net-zero of an industrial sector [5]. It is thus important to understand how this uncertainty has been resolved in the past to accelerate green transitions. Third, as we elaborate in the discussion, several hard-to-abate sectors (e.g., freight, shipping, aviation, machinery) share the characteristics we deem crucial to understanding the dynamics of clean innovation in the automotive sector, which makes this case study important to learn from.

This paper is the first quantitative study of the innovation dynamics between FCEVs and BEVs. In a nutshell, we argue that carmakers' and national policy-makers' choice between FCEVs and BEVs was a global coordination problem. The technological complementarities involved in developing transport systems based on either fuel cells (FCs) or battery storage implied that a single technology would emerge in the globally integrated market and production network for lightweight vehicles. We show that carmakers hesitated for a long time between these two technologies, focusing for a period mainly on FCs before this technology experienced a reversal of fortune as the industry shifted its focus to batteries. In the absence of global sectoral-level coordinating institutions to collectively choose a low-carbon technological pathway, a fortuitous wave of battery innovation coming from outside the sector, especially electronics, led the industry and policy-makers to eventually focus on BEVs.

Our analysis uses patent data and supply-chain data to track innovation targeted at FCs versus battery technologies over time for carmakers, their subsidiaries, and their suppliers. We also use patents for these technologies in the whole economy to understand how trends outside the industry influenced carmakers. Our analysis examines the role of national innovation policies in steering the industry's choice. We use data on public RD&D investments and compile a new dataset on countries' national strategic plans for clean vehicles. These national policies were attempting to coordinate firms across relevant sectors at the national level. They could potentially have played a role in solving the global coordination problem. Yet, pre-2010, they were globally uncoordinated: different countries were pushing for different technologies. It is thus no surprise to find that they were not able to lead carmakers' choices.

Our analysis speaks directly to the literature on directed technological change and the environment [6, 7], and the literature on induced green innovation [8, 9]. The basic theory focuses on the double market failure pertaining to the positive knowledge externalities and the negative carbon externality, justifying both technology-push policies (e.g., subsidies) and demand-pull policies (e.g., carbon tax). It ignores technological complementarities and the associated coordination problems they pose [but see 10, 11], issues long highlighted by strategic management scholars [12]. It also ignores the mismatch between the national scale of innovation policies and the globalized organization of production of many industries [13].

This quantitative case study contributes to the extensive empirical research on clean technological transitions [14]. Previous literature predominantly explores the evolution of the solar and wind energy industry [15–17]. The shift to electric vehicles presents a distinct challenge, as it demands a foundational change in the technology used by established firms – a situation mirrored in many hard-to-abate sectors. We also contribute to the discovery of factors that affect the speed of green technological change [18].

We contribute to the currently small body of work analyzing technological change and innovation in the transition to Electric Vehicles (EVs), e.g., focusing on the impact of California's early technology forcing mandate [19], the "hype cycle" around successive technologies [20], the entry of Tesla [21], and institutions supporting EV innovation in China [22]. Finally, our study adds new insights to the strand of research focusing on the importance of knowledge spillovers [23], including cross-sectorally [24, 25], and of learning dynamics [26, 27] in these technological transitions.

1 A Global Coordination Problem

The transition to clean car technologies displays features of a global coordination problem. Carmakers, tier 1 suppliers, and policy-makers in major markets all need to converge on a common direction of technological change before large investments to scale up production and infrastructure can take place. We argue that two key dimensions determine the extent of the coordination challenge faced by firms: 1) the degree of technological complementarities and 2) the degree of market integration.

Strong complementarities in technological components. Figure 1a illustrates that road transport systems based on FCEVs and BEVs require very different sets of complements [28, 29]. First, these two technologies are based on different storage technologies: a fuel cell stack with a hydrogen storage tank on the one hand and a battery on the other. The storage technology also needs to be integrated into the car architecture and requires a different supply chain for its assembly and constituent parts (specific cathodes, anodes, electrolytes, and separators), thus requiring complementary investments by competent suppliers. This means there is very low modularity in the design options for clean car technologies. A large literature in the management of innovation has shown through many case studies of technological change that players in a low-modularity technological system need to coordinate on compatible technological choices as they innovate [4, 30, 31].

Each technology also requires a different upstream energy supply and downstream energy distribution infrastructure. BEVs are initially compatible with the existing grid as long as a sufficient charging infrastructure exists. FCEVs require a supply of hydrogen and pipelines and fueling stations for its distribution. Thus, the technological characteristics of clean cars call for tight coordination between the innovation and technological investments of carmakers, suppliers, and an economy's energy system. Yet, the car industry is a globally integrated market with shared suppliers.

A globally integrated market with shared suppliers. The majority of automobile manufacturers operate in numerous countries and tap into a shared network of international suppliers (see Methods). Figure 1b shows the global tier-1 supplier network for the 10 largest carmakers. White nodes are suppliers, and their size is proportional to the number of links to carmakers. We see that the network is tightly integrated: half of all carmaker pairs in the whole network share a supplier. The overall modularity is very low (m = 0.3); thus, there is limited scope for groups of firms working independently from each other (also see Supplementary Table **??**).

These network characteristics reflect a general movement towards the global integration of production, which started in the 1970s [32] and accelerated in the 1990s [33], allowing for economies of scale and scope, lower labor costs, and ultimately lower consumer prices. In the context of the automotive industry, this organization of production came long after carmakers standardized the ICE design and its component parts, thus allowing vertical disintegration [34]. Innovation in this network favors incremental improvements to individual components, easily outsourced to the network of global suppliers.

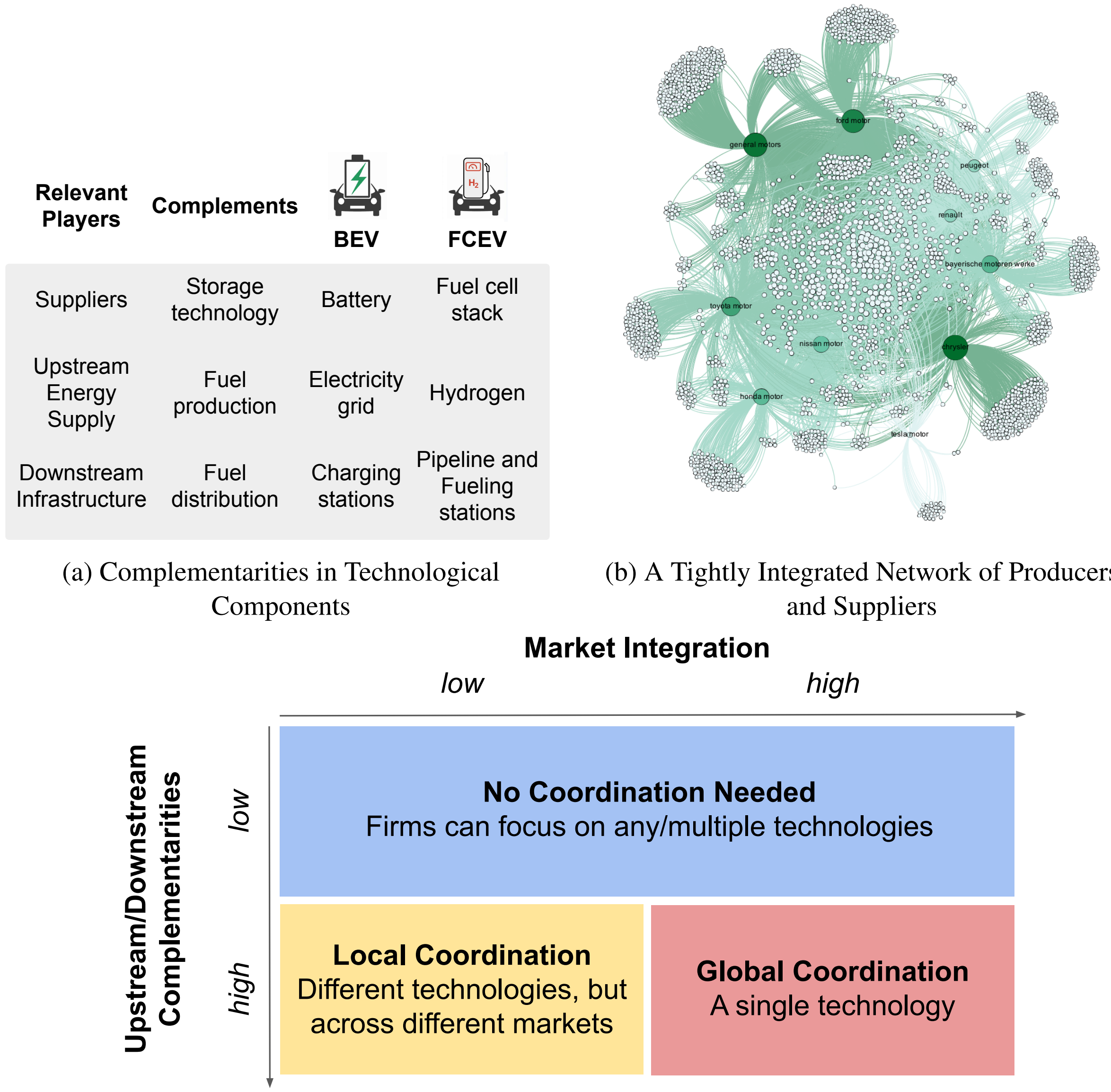
When can several technologies co-exist? Figure 1c brings together the two dimensions discussed above (technological complementarities and the degree of market integration) to make predictions about the scale of coordination needed to enable investments in a radically new technology. At one end, in the absence of complementarities, no coordination is needed, and firms can pursue multiple technological options. In the presence of complementarities, relevant players must coordinate. If different players are active in different markets (low market integration), they need to coordinate locally, and players can coordinate on different technologies across different markets. However, if market integration is high, as we argued it is in the car industry, all main players will need to coordinate on a single technology.

In prior work, we provided a model of the micro-foundations for the predictions in 1c [35]. We model a situation in which there are strong technological complementarities between carmakers and shared suppliers. We show that in this situation, technological uncertainty (i.e., lack of coordination regarding whether the industry is developing option A or option B) reduces the incentives of car manufacturers and suppliers to innovate on clean technologies. More broadly, history offers numerous examples of industries faced with multiple technological options that, due to their lack of modularity, were incompatible, leading to the dominance of one option[36, 37].

Tesla and Hybrid Cars Viewing the shift to clean cars as a global coordination problem provides valuable insights into two notable success stories: the development of hybrid cars such as the Prius and the emergence of Tesla as an early player in the electric vehicle market. Indeed, hybrid cars offer a strategy to radically reduce the upstream/downstream complementarities needed to develop EVs. We can thus place the hybrid in the upper quadrant of Figure 1c. Early hybrids used batteries with low performance, which were still poorly integrated into the car and didn't require charging infrastructure, but this poor performance was "hidden" by the ICE. Gradually, as the battery and the integration of the battery in the car improved, hybrids could rely more heavily on electric propulsion [38]. Tesla, meanwhile, was the first carmaker to signal the readiness of Li-ion batteries for long-range cars. They did so by targeting the luxury car market and vertically integrating supply, creating a fairly separate market [39]. We can thus place Tesla in the lower left quadrant of Figure 1c.

To conclude, the theory in Figure 1c poses a puzzle: in the absence of an international institutional process to coordinate technological choice, how did the automotive industry converge on BEVs? This paper examines two ways in which coordination could happen: 1) through national policies and 2) through cross-sectoral spillovers that exogenously provide some of the technological complements depicted in Figure 1a.

We note here that it is unlikely that coordination on BEVs happened because a critical mass of players saw it as unambiguously superior to FCEVs. In fact, FCEVs seemed like a closer substitute to ICEs (due to range and ease of refueling) [28]. Many government and industry reports enthusiastically reported fast improvements in the cost and performance of fuel cells and expected market competitiveness by 2015. The general consensus in the industry around 2005 was that FCEVs would be the technology for long-range vehicles ($>$50% of the market), while BEVs would cater to short-range urban compact cars.



(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 how tightly integrated the network of carmakers and tier-1 suppliers is. Green nodes are the ten largest carmakers; white nodes are suppliers, and their size is proportional to the number of links to carmakers. Figure 1c combines the two key dimensions, technological complementarities and the degree of market integration, to make predictions about the scale of coordination needed to enable investments in a radically new technology.

Figure 1
Choosing What Type of Clean Car to Develop is a Global Coordination Problem

2 Fuel cells experienced a reversal fortune while battery patenting took off.

We begin by examining the innovation strategies of carmakers, analyzing patent data for both car manufacturers and their subsidiaries (see Methods). Our data reveal a significant increase in patents related to clean car technologies since 1990, surpassing patents related to internal combustion engines around 2000 (See Supplementary Figure **??**). However, this apparent transition to clean car technologies conceals distinct trends between FC and battery technologies (see Figure 2a).

At the end of the 1990s, fuel cells became the main storage technology carmakers focused on, and the number of FC patents increased rapidly until around 2004. But then FC experienced a stark reversal fortune: the number of patents plateaued and abruptly decreased after 2007. During that same period, battery patenting accelerated. These trends are consistent with the documented cycles of hype and disappointment in US media around different alternative fuel vehicle technologies [20].[1]

The reversal occurred alongside sustained growth in innovation on electric vehicle (EV) patents (see Supplementary Figure **??**), which focus on electric propulsion (e.g., e-motors, regenerative braking, control units) and are relevant to all electric vehicles (i.e., battery or fuel cells). Patents related to hybrid vehicles increased significantly throughout but have plateaued since 2008. On the other hand, we note the low level of patents on hydrogen production and distribution, a key complement to fuel cells.

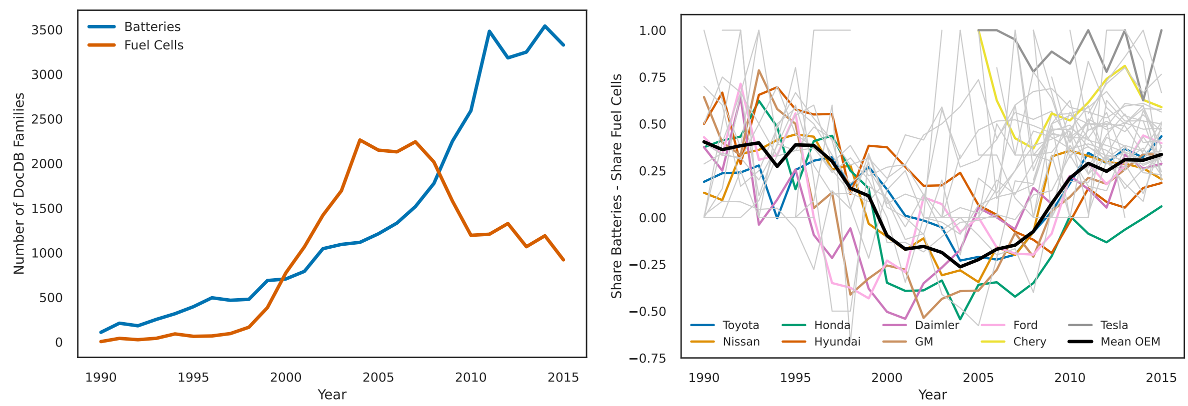
Remarkably, carmakers' shift from FC to battery is globally synchronized: almost all large carmakers went through a similar increased focus on FC and then battery (see Figure 2b). Some carmakers initiated their shift earlier than others,[2] but overall, laggards follow leaders with a lag of no more than five years.

As a result, the sector looks "coordinated," which is consistent with the arguments in the previous section, mainly that, for a technological transition of this nature in a globally integrated industry, firms would focus on the same technology. We see no evidence of a modular pattern of technological development whereby different companies in different countries could experiment and develop alternative solutions.

Figure 2b also shows that new entrants (e.g., Tesla and Chinese carmaker Chery) avoided the era of technological uncertainty that incumbents had to navigate and entered once the industry as a whole was converging on battery.

[1]Analysis of US media shows an initial wave of enthusiasm for methanol and natural gas, then in the mid-1990s, a hype cycle around the battery electric vehicle, superseded by a wave of enthusiasm for the hydrogen fuel cell and biofuels, and coming back to battery electric vehicles around 2007.

[2]For example, Daimler led the charge on fuel cells in 1994, followed by GM and Ford. Nissan and Honda, meanwhile, show a clear shift closer to 2000.



(a) Fuel Cell and Battery Patenting

(b) Selected carmakers

Figure 2

Patent Families of Carmakers: A Reversal of Fortune for Fuel Cells

Note: Panel 2a plots the number of patent families filed by at least one carmaker over time related to battery or fuel cell technology. Panel 2b plots for each carmaker the difference between the share of battery and the share of fuel cells in their clean car patent portfolios. The selected labeled carmakers are those with the highest clean car patenting output, plus two entrants: Tesla and Chery.

3 The absence of policy coordination on FCEVs may have favored BEVs.

Starting in the 1990s, policymakers attempted various ways to push new technologies and enlist industrial players to develop them. We document these efforts first using national-level data on public RD&D funding and second by compiling data on policymakers' strategic orientation, which is often described in official documents such as roadmaps or strategic plans (See Methods).

Strategic orientations formulate pathways and objectives for the development of new technologies in an effort to coordinate innovation and development efforts across national laboratories, industrial players, and other key stakeholders. Given our theoretical focus on the coordination challenges of technology transitions, these strategic policy frameworks are potentially important inputs in the policy mix as they attempt to minimize coordination problems, albeit only at the national scale. For each strategic orientation policy, we record the technology it targeted.[3]

Figure 3a represents the history of strategic orientations in the transition to clean vehicles by country. We note the lack of global alignment on the choice of technology before 2010. Although national policies attempted to coordinate actors by providing strategic orientations, these orientations diverged internationally, providing no clear global pathway.

By 2010, however, national policies had converged on BEVs, often as a medium-term solution, with some countries still planning to switch to FCEVs in the long term. The USA, France, and Germany chose this path in 2008, and Asian countries followed in 2010. The UK, meanwhile, stuck for another several years with a technology-neutral strategy.

[3] We leave aside demand-pull policies (e.g., consumer subsidies or emission standards) because their goals are technology-neutral. In contrast, RD&D support and strategic orientation are technology-push policies that deliberately target specific technologies.

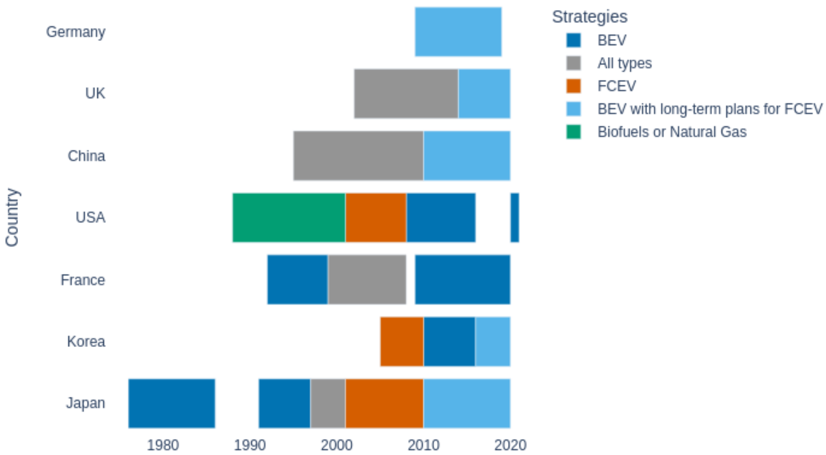
Figure 3b shows the evolution of public funding for RD&D over time by country for fuel cells and hydrogen and electric energy storage. We note that all countries' spending on FC steadily increased from the end of the 1990s to 2008. It then declined and stabilized to about half of its peak. On the other hand, spending on electric storage presents a very different pattern: it remained flat until 2008 but then took off in most countries, particularly China.[4]

Next, we investigate the relationship between firm-level patenting and policies, using measures of policy exposure constructed at the firm level (see Methods). Figure 3c displays the average patenting trend and policy exposure of carmakers. This helps us understand when innovation occurs in relation to policy shifts. We also carry out firm-level regressions using as outcome variable the difference between the share of battery and the share of FC patents in carmakers' clean portfolios (see Methods). This analysis gives a clearer view of how policy timing affects firms' emphasis on battery and FC.

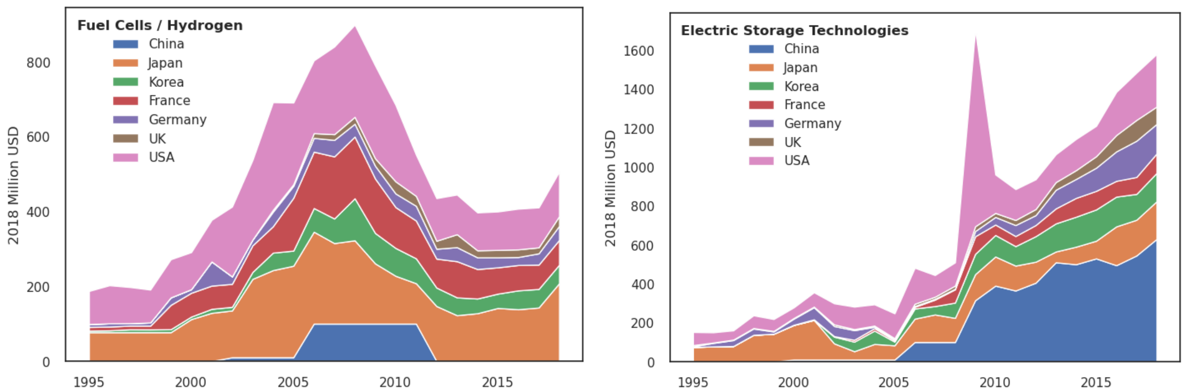
In Figure 3c, carmakers' FC patenting appears to increase at the same time as exposure to FC orientation (coming from the US, Japan, and Korea's policies). However, public spending on RD&D tends to follow the trends in companies' innovations with a lag. Regression results support this observation: higher exposure to RD&D spending on FC at $t+1$ (and to some extent to FC orientation) correlates significantly with a decreased focus on battery relative to FC at time t. This suggests that policies aiming to promote FC did not guide company decisions but rather responded to them.

Figure 3c also shows a clear uptick around 2008 for all variables related to battery, suggesting that both carmakers and policymakers shifted strategy simultaneously. The regression results further suggest that when companies were more exposed to battery national orientations in a given year, they became more likely to focus on battery patents the following year. This relationship persists even when including firm and year fixed effects. Furthermore, firms exposed to higher public RD&D spending on electric storage the year before were also more likely to focus on battery patents—this effect though is not robust to including firm fixed effects. Simply put, a combined effort of strategic planning and research funding set the stage for companies to prioritize battery innovations.

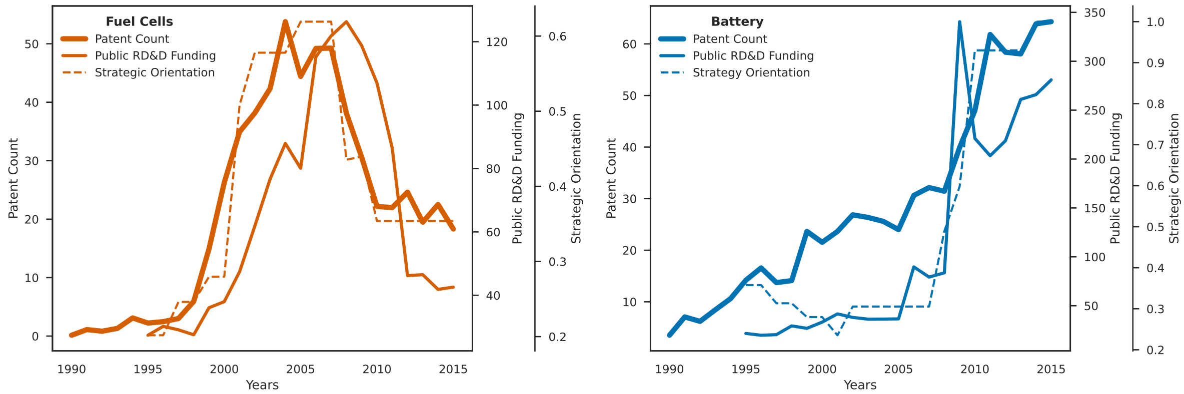
[4]The USA's significant increase in 2009 is due to the American Recovery and Reinvestment Act.



(a) Country-Level Strategic Orientation



(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
Fuel Cells vs. Battery Policies

Note: The figures describe the evolution of strategic orientations and public funding for RD&D over time by country for fuel cells and hydrogen and electric energy storage.

4 Significant innovation on batteries happened outside the industry and spilled over to carmakers.

Next, we extend our dataset to include all clean car related patents in PATSTAT, beyond just carmakers and their subsidiaries, and classify patents according to the industry of the filing firm (See Methods). This allows us to study cross-sectoral spillovers.

Figure 4a shows that the Motor Vehicle industry (all carmakers, their subsidiaries, and parts manufacturers) only captures between 5 and 15% of all battery-related patents. This highlights the importance of other actors and sectors in the economy for pushing the battery technology frontier. The main other players are industries related to information technologies and electronics. In fact, we see that by the time carmakers decided to accelerate their efforts on battery around 2005, these sectors had been patenting at a high rate for many years; the performance of batteries had already dramatically improved, and their cost had fallen tenfold. It thus seems that trends exogenous to the car industry created the potential for a technology push toward batteries.

A very different story emerges for fuel cells. In this case, the Motor Vehicle industry is the dominant player; it is responsible for almost 35% of all FCs patents around 2005, just before the reversal. Other sectors play a more minor role and largely follow the boom-and-bust cycle of carmakers. Notably, there is little innovation in sectors where FCs and hydrogen have many applications, such as other transport (e.g., maritime and air) and machinery.

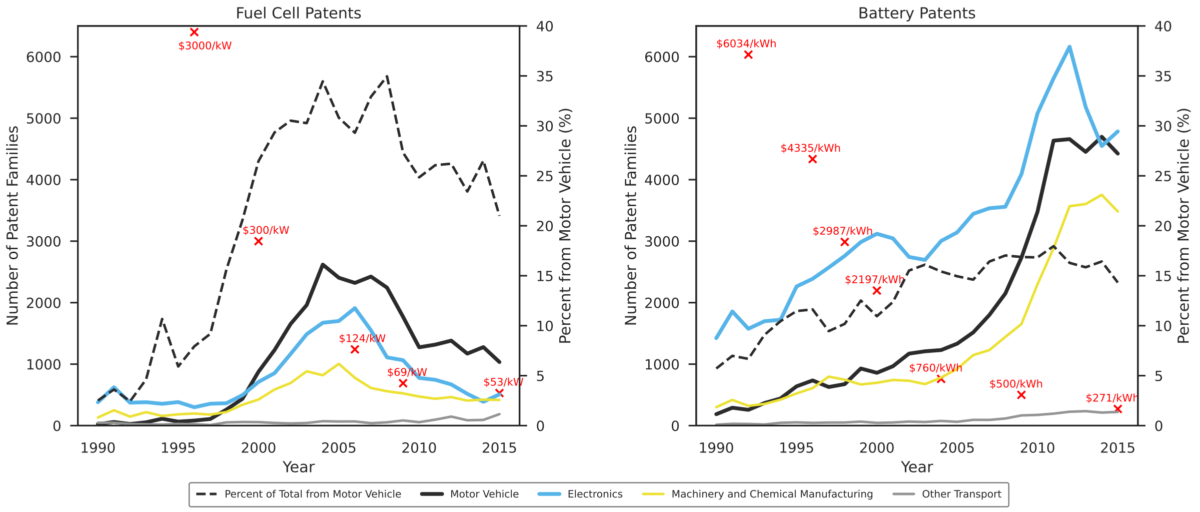
To underline the importance of these sectoral trends, we use patent backward citations to show that carmakers when working on these storage technologies, draw more on the pool of knowledge generated outside of the industry than within (See Supplementary Note **??**). We find similar results when constructing a measure of *expected* spillovers that controls for changes in carmakers' patenting activity [24].

Finally, we examine innovation dynamics among carmakers' suppliers (see Methods). As highlighted before, suppliers play a key role as providers of complementary inputs, and as a result, supply-chain relationships can serve as important vectors of cross-sectoral spillovers that may benefit a particular technological direction.

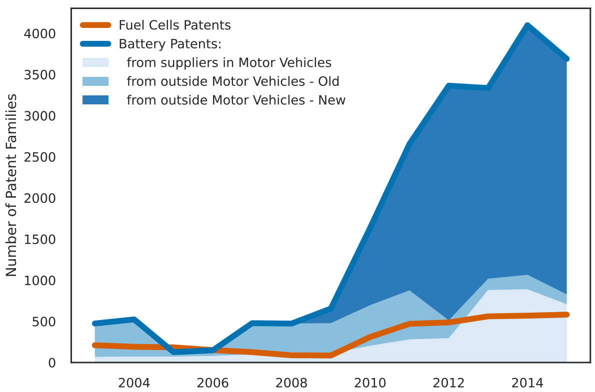
Figure 4b examines patenting trends for "active" suppliers, i.e., suppliers with a documented supply relationship with any of the carmakers in year t. We observe a rapid acceleration in battery patenting among suppliers around 2008, surpassing fuel cells by a considerable margin. This surge is due to the influx of new battery-competent firms into the supply chain rather than being driven by drastic changes in the strategies of existing suppliers.

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. We see that in the period 2008-2013, carmakers made new relationships with firms with larger stocks of battery patents. In contrast, these new suppliers do not have large FC patent stocks, and in the boom years of FC innovation, we do not observe new relationships with FC-competent suppliers.

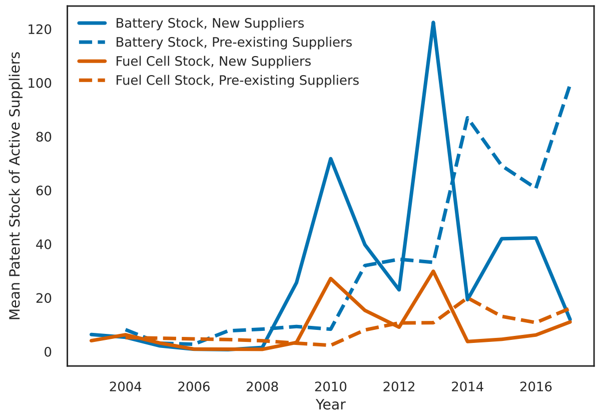
This is evidence that cross-sectoral spillovers in favor of batteries happened not only through diffuse knowledge spillovers but also by enabling carmakers to rewire to battery-competent suppliers coming from outside the automotive industry. Moreover, this happened at the same time as the global convergence of technology policy on batteries and carmakers' own acceleration of R&D efforts on batteries. Thus, we see here that the take-off of BEVs was facilitated by policy coordination, knowledge flows from related technologies, and complementary knowledge in the supply chain. These conditions did not align for FC.



(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 (See Methods). Figure 4c shows patenting trends for new and "old" suppliers, i.e., suppliers with active links to carmakers prior to 2009. We see these suppliers have much lower battery patenting.

Discussion

Our analysis demonstrates that global car manufacturers experienced two decades of substantial technological uncertainty, primarily concentrating on FCs before a consensus was reached on BEVs. We contend that these innovation strategies are symptomatic of a larger global coordination issue. Several key observations substantiate this interpretation.

First, we have shown that carmakers attempt to move synchronously rather than pursue distinct technological pathways in regional markets. Secondly, there is little investment in infrastructure and production capacity before resolving the uncertainty (i.e., the coordination problem).

Finally, only when policies begin to favor BEVs do trailing carmakers and traditional suppliers intensify their efforts toward clean car innovation. This suggests that without coordination, a protracted period of technological uncertainty can slow down the transition.

Despite the lack of coordination, both industry and policymakers ultimately settled on BEVs, but this consensus was not a premeditated strategy. Instead, it unfolded unexpectedly due to fortunate cross-sectoral spillovers, a byproduct of billions of consumers buying smartphones, laptops, and power tools.

Conversely, the failure of FCs to gain traction can be attributed to multiple coordination failures: inconsistency in policy across markets, inadequate sectoral coordination with upstream hydrogen supply, and an absence of collaboration with sectors that could have concurrently worked on fuel cells, generating broader knowledge spillovers.

This case study provides valuable insights into technological change, especially concerning decarbonization challenges. Industries such as shipping, aviation, freight, and possibly steel and cement, share similar characteristics with the automotive industry. They are considering a diversity of low-carbon alternatives [40], exhibit interdependencies between upstream and downstream activities, and operate within globally integrated markets.

The key insight is that the need for complementary innovations and investments may justify an institutional process to coordinate on the choice of a technology. Otherwise, it might take an extended period for consensus to form around a specific technology [20]; convergence may also hinge on serendipitous technological advancements that give a distinct advantage to one option over others. The market then also becomes the primary arbiter, selecting the most viable option based on market readiness. However, the most market-ready technologies are not necessarily the "best" from a whole-system, long-term perspective, a point long emphasized by scholars focused on technological path dependence [41, 42]. For example, some believe that hydrogen, currently seen as important for decarbonizing several industries, could eventually outperform batteries in cars [43].

Thus, once sufficient experimentation has established confidence in a technology's potential, there may be a case for policy intervention to coordinate actors around a specific technology, forming coalitions spanning major markets. Although we empirically document a mechanism underlying the necessity for global coordination to speed up the transition to clean technology, we also want to draw attention to its potential pitfalls, chiefly the hazard of choosing technologies that may prove sub-optimal in the long run.

In the event that industry leaders and policymakers choose to establish institutions that favor specific technologies, they must heed the key lessons learned from the automobile industry. The first is the crucial role of cross-sectoral complements and spillovers in allowing a new technological system to take off [25, 44]. Identifying complementarities and encouraging innovation across sectors should be significantly more effective than sectorally isolated innovation programs.

The second is the difficulty of inducing technological change with national policies alone in a global industry. Our case 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, 46].

Methods

Sample of Car Manufacturers and Suppliers. We compile a list of car manufacturers from Marklines, an automotive industry portal. We identify a total of 71 firms that we manually match, based on name, to Orbis identifiers (BvD ID). We also use Marklines to collect sales information by carmaker, year, country, and type of vehicle (ICE, electric, hybrid, hydrogen). See Online Appendix Section **??** for summary statistics.

With many subsidiaries, the corporate structure of car manufacturers can be complex. We use data available on Marklines to aggregate brands under the largest possible owner. For example, the GM group not only encompasses the GM brands but also Opel and Vauxhall. On the other hand, the firm Renault encompasses Dacia and AvtoVAZ but not Renault Trucks, which became a subsidiary of Volvo Group in 2001. To ensure we include as many potential subsidiaries as possible, we use Orbis to obtain the BvD IDs of all the subsidiaries connected to our sample of carmakers. We also reflect changes in ownership structure over time.

Suppliers of Carmakers. To document trends about car manufacturers' suppliers, we use data from Factset Revere, a database that covers relationships such as supplier-buyer for a large number of public and private firms between 2003 and 2017. First, we connect our sample of car manufacturers to Factset by name matching. We then extract the buyer-customer relationships of carmakers over time and use name-matching again to associate Factset suppliers to BVD IDs to collect suppliers' patent information.

Patenting of Car Manufacturers and Suppliers. We then collect patent information for these firms using PATSTAT Global Spring Edition 2022. To do so, we use Orbis IP, which links patent identifiers and BvD IDs. We aggregate patent information such that any patent filed by any of the subsidiaries is counted toward the patenting activity of the carmaker that the subsidiary belongs to.

We use CPC and IPC codes to identify the number of patents that relate, in particular, to "Clean Car" technologies: batteries, fuel cells, hybrid vehicles, electric vehicles, hydrogen, energy storage, and biofuels. To do so, we harmonize and update the list of codes provided by prior studies [23, 47–49] (See Supplementary Section **??**).

We aggregate patent applications at the level of DOCDB patent families; these are collections of patents that are considered to cover the same technical content and, therefore, represent the same invention. This helps us to avoid double-counting inventions.[5] We date families by 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 going back to 1980. We discount stocks by 15% each year following prior work [50].

Patent citations. Using PATSTAT, we aggregate information about which patents are cited (or citing) and when. In particular, we classify the citations according to their technology type (e.g., battery) and firm (e.g., carmaker or non-carmaker). Following prior work, we use patent

[5]Several patents are typically filed about the same invention because the different applications may cover slightly different claims (about the same invention) or contain precisely the same claim but are filed in different countries.

citations as a proxy for knowledge spillovers [51]. We also compute a measure of *expected* spillovers which, unlike the basic counts of citations, control for contemporaneous changes in OEM's patenting activity [24]. For technology k in year t, this is computed as:

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

where $Citation_{k,a}^{OEM \Rightarrow non-OEM}$ is the number of citations made by OEMs to non OEMs regarding technology k with a year of lag.

Other Firms Patenting in Battery and Fuel Cell. We use Orbis to extract information about industry codes (4-digit NAICS code) of any firm patenting in transportation. This allows us to categorize firms into either "Motor Vehicle" (which combines firms with NAICS codes 3361, 3362, or 3363. We include in this category all the car manufacturers, but also subsidiaries and suppliers), "Electronics" (which we define as the combination of 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) and "Others".

Policy variables. For public RD&D support, we use data from the IEA Energy R&D dataset, which provides data on hydrogen and electric storage for all countries except China for the period 2004-2018. Data for China was obtained from Zhang *et al.* [52]. We conducted archival work to extend the time series back to 1995 in each country.

To build the dataset on strategic orientations, we identified the most overarching strategic orientation policy documents for road transport in each period for each country and coded which technology they target or if they remain technology neutral. Supplementary Section **??** provides the list of framework policy documents from which we inferred a strategic orientation. An example is the National Energy Policy by President Bush in 2001, which sets out clear technological priorities for each sector in the energy system.

To build country-level measures, we numerically code the strategic orientation data as follows. If a country has a clear strategic focus on technology x in year t, we code this as 1. If it does not target technology x, we code this as 0. If it targets technology x but without prioritizing it, we code this as 0.5 (e.g., the strategic orientation value in China is 1 for batteries because the government gave clear targets for developing BEVs in the short-term, and it is 0.5 for fuel cells because the government has a long-term plan for developing fuel cells and hydrogen in transport).

Then, for both RD&D spending and strategic orientation, we compute a firm's exposure as a weighted mean of national policies, where the weights are the share of the firm's sales in that country in 2004 (obtained from the automotive industry database Marklines)[6]. Finally, we run a series of regressions to examine the relationship between policies and patenting more closely. Our primary outcome variable is the difference between the share of battery and the share of FC in firms' clean patent portfolio. Results are shown in Supplementary Subsection **??**.

[6]We would ideally use historical shares from 1995, but this data is not available pre-2004.

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