INTERNATIONAL DIFFUSION OF SUSTAINABLE INNOVATIVE AUTOMOBILE ENGINE TECHNOLOGIES: A MANUFACTURERS' STRATEGY

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Abstract

Concerns regarding the health of the planet and its economies have led to an increased focus on sustainable new technology (SNT). However, the diffusion of SNT-based products appears uneven globally. Research informs that diffusion can be influenced by multiple factors, including country policies and private sector initiatives (Albino et al., 2014). This study uses a top management team (TMT) perspective (Hambrick & Mason, 1984) to analyze auto manufacturers' worldwide sales of electric vehicles (EVs) to understand and explain this uneven diffusion. The data indicate that individual sub-categories of EVs are developing at different rates and that significant differences exist among countries and manufacturers. These observations suggest that not all sub-categories of EVs are equal in the minds of consumers, manufacturers, and governments. Mandates from the European Union (EU) and other entities that no new internal combustion engine (ICE) vehicles can be sold after 2035 are forcing all parties in the automotive industry to work earnestly to develop EV-related technology. From a policy perspective, this research shows that government policy can work to both motivate consumers to purchase EVs and manufacturers to produce EVs. In addition, we identify avenues for future research.

Keywords: Sustainability, Diffusion, Innovation, Technology

Authors' individual contribution: Conceptualization — L.J.Z. and M.J.; Methodology — L.J.Z.; Formal Analysis — L.J.Z. and M.A.T.; Data Curation — M.J.; Writing — L.J.Z. and M.A.T.; Visualization — M.A.T.

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1. INTRODUCTION

Ample literature exists concerning how innovation is developed and benefits firms and societies (Davila et al., 2012; Kline & Rosenberg, 2010). However, a less well-researched aspect of innovation is understanding the factors influencing the global diffusion of these innovations. It is diffusion, or the broad acceptance and use of innovations in society, rather than the innovation itself, which provides the engine for economic growth and increases in productivity (Hall & Khan, 2003).

Research on the causes and effects of development and diffusion of innovation informs that they can be influenced by multiple factors or levels, including country policies, historical events, and private sector initiatives (Albino et al., 2014). Shao et al. (2020) showed that environmental regulations impacted enterprise innovation behavior. Heredia et al. (2020) argue that a stable institutional environment is necessary for firms' research and development (R&D) investments in innovation. Furthermore, firms can adapt innovations to the context to address world problems. For example, various antiviral drugs were repurposed to treat COVID-19 (Ardito et al., 2021).

Growing concerns regarding the planet's health are giving rise to a focus on eco-friendly and sustainable technology (Beyer & Urpelainen, 2013; Hugh & Clouse, 2018; Popp, 2011; Schotter et al., 2019). Environmental sustainability is of global interest. The knowledge and development of sustainable technologies are growing worldwide (Wagner, 2007). Thus, it is no longer relevant to only study the development and diffusion of new technologies, but specifically to examine the factors that affect the development and global diffusion of sustainable new technologies (SNTs).

Studies on consumer adoption of electric vehicles (EV) and other SNTs assume that these new technologies can reduce environmental problems while boosting economic growth (Khattak & Khattak, 2023; Khayati & Kang, 2020). It is highly desirable that innovations that improve the planet's health diffuse widely and rapidly (Beyer & Urpelainen, 2013; Popp, 2011). Hence, understanding the factors that affect the global development and diffusion of SNTs, such as EVs, is critical. However, the diffusion of SNT-based products appears uneven globally. This study analyzes auto manufacturers' worldwide sales of EVs to investigate and explain this uneven diffusion. We believe this to be critically important as the EV market is expected to reach roughly 40 million vehicles sold by 2030 (Krishnamurthy et al., 2022).

Top management teams (TMTs) of firms make strategic decisions to develop technologies and enter markets based on their interpretation of the general environment, their competitive positions concerning resources and markets, and their goals and vision for the firm (Hambrick & Mason, 1984; Hambrick et al., 1996). Despite extensive literature describing how TMTs affect firm direction and decision-making, we do not have a TMT perspective of the global diffusion of SNT, a gap we start to fill with this paper. Adding a TMT perspective provides insight into corporate workings in the diffusion of SNT. This insight would be helpful for policymakers, researchers, practitioners, and educators.

We study the global diffusion of SNT via a focus on alternative automotive propulsion technologies (electric and hybrid vehicles), otherwise known as EVs, for the context of our research. The automotive industry has undergone significant technological innovation due to a shift in populations' and governments' attitudes towards a more sustainable and "green" approach to life. This shift led to multiple recent innovations in automobile propulsion methods, and we believe these innovations are amenable to adoption globally. Thus, alternative propulsion technologies for automobiles are adequate for researching the global diffusion of SNT.

This paper employs a TMT perspective to investigate and explain global trends in manufacturers' longitudinal EV sales using data from 89 countries between 2008–2017, together with recent research and articles. This research looks to make several contributions to the literature: 1) discern what is driving uneven regional and international growth rates of categories of EVs, 2) understand how policy-makers can facilitate growth in the EV marketplace; knowledge that can then be put to use in this and other industries, 3) gain insights as to how differences in local conditions influence the strategic decisions of firms' TMTs, and 4) identify future avenues of research.

Our analysis indicates that individual sub-categories of EVs are developing at different rates and that significant differences exist among countries and manufacturers. These observations suggest that not all sub-categories of EVs are equal in the minds of consumers, manufacturers, and governments. From a policy perspective, this research shows that government policy can work to both motivate consumers to purchase EVs and manufacturers to produce EVs. In addition, we identify avenues for future research.

The rest of the paper is structured as follows. Section 2 reviews the relevant literature. Section 3 describes the methodology used to analyze EV propulsion systems and market adoption of EVs. Section 4 presents trends observed in global EV sales. Section 5 discusses the findings. Section 6 contains our conclusions.

2. LITERATURE REVIEW

2.1. Diffusion of innovation

The study of innovation diffusion began more than a century ago (De Tarde, 1903) and has continued steadily through today (Guerrero & Martínez-Chávez, 2020; Rogers, 1962; Ryan & Gross, 1943). While most diffusion studies focus on innovation adoption within a country or in a small region, there are global studies from which we can draw lessons. Ciruelos and Wang (2005), using data from 57 countries (1988–2001), observed that foreign direct investment and trade serve as relevant channels of international technology diffusion. Similarly, Messinis and Ahmed (2013) examined data from 70 nations (1970–2003), concluding that valuable human capital skills facilitate technology diffusion. Reddy (2017) declared that economic liberalization has opened up some formally protected domestic markets and increased global competition in these markets, creating both a driving force and an enabling factor for technological globalization. Finally, Frimpong et al. (2020) indicated differences between countries concerning the effect of intrinsic traits in explaining consumers' attitudes toward adopting new technologies, such as mobile banking.

From the perspective of individual firms participating in innovation and diffusion, studies have examined firm-level variables related to structural (e.g., firm age, size, management systems), strategic (e.g., R&D, markets served, entrepreneurial orientations), and relational features (e.g., internal communication modes, incentives) of firms to explain variations in firms ability and drive to manage technologies and the development of inventions into innovations successfully (Ardito et al., 2015; De Clercq et al., 2015; Dosi & Nelson, 2010). In addition, growing concerns over carbon footprints and competitive pressures are forcing auto manufacturers to adopt sustainability practices (Gong & Zhu, 2015; Schotter et al., 2019). One such study has examined how firms might develop a sustainable development mindset among their employees to better address development practices focused on the greater good (Yeung, 2019).

SNTs utilize natural resources efficiently and significantly reduce negative ecological impact. Sustainable technologies include, among other things, solar cells, wind turbines, and geothermal energy. Jaiswal and Zane (2022) examined country-level factors affecting EV diffusion. Their results suggest a significant correlation with the development status of a country, its government type, the society's focus on sustainability, the country's innovation focus, and its levels of diffusion of other SNTs. The current study builds upon the work of Jaiswal and Zane (2022), and others, by examining the global diffusion of EV technology from an original equipment manufacturer (OEM) perspective. Next, we discuss TMT theory and its potential to impact firms' EV technology decisions.

2.2. The top management team

Each firm's executive team makes the decisions regarding engagement in the EV sector. This TMT chooses among various entry technologies (e.g., hybrid versus battery only), the timing of such entries, and the mode of entry, among many other things. As such, factors influencing these decisions should be examined. Much of TMT research focuses on two elements impacting TMT decision-making. The first focuses on heterogeneity within the TMT (internal factors) and its impact on the firm, while the second focuses on the influence of environmental factors (external factors).

Scholars have theorized about the influence of the TMT on innovation in varying contexts. Their research argues that TMT members are key in formulating strategy, especially regarding the hard decisions of simultaneously coordinating activity in the industry and maintaining firm-specific capabilities required to differentiate (McGrath et al., 1992; Teece, 2007). In addressing the firms' competitive strategy in technology-intensive industries, Teece (2007) argued that the success of a technology-based enterprise would depend largely on managers' "uncommon foresight and the ability to shape outcomes" (p. 1332) Inspired by this insight, we discuss the elements of the TMT that may contribute to a firm's decisions regarding SNT.

Heterogeneity within the TMT and its relationship to firm outcomes have been extensively examined within the literature (Buyl et al., 2011; Cannella et al., 2008; Fox et al., 2022; Hambrick & Mason 1984; Hambrick et al., 1996; Richard et al., 2021). In seminal work focused on synthesizing top team research into an upper echelon's perspective, Hambrick and Mason (1984) developed a strategic choice model centered on bounded rationality. The authors suggest that managers' strategic choices are colored by their interpretation of environmental stimuli and that this interpretation is a manifestation of the manager's values, cognitive base, and limited field of vision. Further, these factors lead to selective perception and interpretation when selecting among various strategic choices. By building on this research, scholars predict that creating TMTs with variation in demographics ranging from age and gender (Boone et al., 2004) to work experience (Buyl et al., 2011; Cannella et al., 2008), among other attributes, will influence firm decisions and overall performance.

As mentioned, the work of Hambrick and Mason (1984) helped to ignite research focused on expanding the field of vision of the firm through diversifying the TMT. However, it also brought in the notion that the environment might play a significant role in leadership decision-making. Other scholars have focused on this particular influence on the TMT (Cannella et al., 2008; Decreton et al., 2021). Cannella et al. (2008) find that environmental factors, such as similarity in the physical location of decision-makers, are positively associated with firm performance. Further, these authors find support for the notion that environmental uncertainty positively affects the TMT heterogeneity to firm performance relationship. We believe that these two streams of TMT research play a significant role in firms' decisions not only to adopt EV technology, but also on which form of EV technology to pursue, and then to focus on a strategic plan that takes the firm's competitive position into account.

Research focusing on connections between heterogeneity within the leadership team and firm innovation has extended the research model to include the impact of environmental factors (Qian et al., 2013). Utilizing a sample of technology firms located in China, the authors suggest that uncertainty within the competitive environment may moderate the relationship between leadership team decision-making and organizational innovation. More specifically, the authors predict that during periods of lower competitive uncertainty, decisions affected by higher levels of cognitive conflict (differences in viewpoints and ideas within the team) will lead to more organizational innovation. Conversely, the authors predict that during periods of higher competitive uncertainty, decisions that are impacted by higher levels of affective conflict (interpersonal differences within the team) will lead to more organizational innovation. Both of these predictions were supported. Building on this line of reasoning and research, we extrapolate that environmental factors such as the competitive landscape, government directives, global environmental concerns, and perceptions of which technologies will eventually dominate, permeate executive perceptions and thus affect decisions relating to adopting emergent technologies in the EV sector.

2.3. Electric vehicles

Because of environmental concerns, many view EVs as the core of future automobile transportation (Harrison & Thiel, 2017). The transportation sector currently makes the third-highest contribution to global carbon emissions (International Energy Agency [IEA], 2016) and accounts for approximately half of worldwide oil consumption (IEA, 2015). In Europe, where transportation is the second-largest source of greenhouse gas (GHG) emissions, the European Union (EU) is committed to the reduction of GHG emissions by 40% (versus 1990 levels) by 2035 (European Parliament, 2022). EVs employ an electric motor powertrain for propulsion in place of, or conjunction with, a conventional internal combustion engine (ICE); EVs are viewed as a critical enabler for a low carbon-producing economy (European Parliament, 2022; Rafique & Town, 2019).

EV experimentation began in the 18th century (Guarnieri, 2012) and gained popularity in the early 1900s due to their quiet running. However, the introduction of more affordable ICE-powered vehicles like the Model T, and the low price of gasoline, killed off the fledgling EV market. The second wave of interest in EVs began in the 1930s, but due to limited range and issues with charging time, interest dissipated (Kraft et al., 2021). However, interest has risen as climate change awareness has led to an international push for lower automobile emissions.

EVs are a broad category with variations along a continuum of gas/electric hybrids to exclusively electric. A hybrid electric vehicle (HEV) has an ICE and a supplementary electric powertrain consisting of an electric motor driven by battery power. The battery is charged via recovery of energy that would be lost during braking or directly by the ICE powertrain. With all of the HEV's energy derived from gas or diesel fuel, the HEV can be viewed as a more fuel-efficient car (Schuitema et al., 2013). A plug-in hybrid electric vehicle (PHEV) is a development of the HEV with improved battery capacity and a plug-in charger that enables charging the battery from the electricity grid (Sovacool & Hirsh, 2009) and lessens dependence on the ICE. A battery electric vehicle (BEV) removes the ICE as a power source; it has an all-electric drivetrain powered by a large-capacity battery recharged from the electricity grid (Rezvani et al., 2015). PHEV and BEV technologies are closer to each other than HEV technology. Hence, for some analysis, PHEV and BEV categories have been combined and labeled plug-in electric vehicles (PEV).

As measured by the total number of vehicles, the worldwide market share of EVs is small but growing rapidly. In 2011, the EV market share was only 0.06% of the 51.1 million light-duty vehicles sold in the EU, the USA, and key Asian markets (EC, 2012). In 2017, 3.5 million units were sold, whereas global auto and light commercial vehicle sales were 86.05 million ("Global car sales up by 2.4% in 2017", 2018). In 2021, global EV sales reached a record high of 6.9 million, a 107% increase from 2020 (Cui & Hall, 2022). It is the first time since 2012 that global EV sales doubled in one year. Studies have considered future EV market penetration, with some sources projecting more than 20% annual growth through 2030 (MarketsandMarkets, 2022).

2.4. Market adoption of electric vehicles

Research shows that current EV sales are, to some degree, dependent on support measures such as incentives (Higueras-Castillo et al., 2021) and the availability of charging stations (Costa et al., 2021; Mock & Yang, 2014; Thiel et al., 2015). Another perspective on the current modest adoption figures is that the mass acceptance of EVs relies on consumers' perception of them (Almansour, 2022; Schuitema et al., 2013). EVs pose different behavioral demands on consumers. For example, to run on battery power (PHEV or BEV), drivers need to get used to plugging into the electricity grid and charging the battery while it is not in use, a situation that may require planning for their next drive (Axsen et al., 2012). Other driver concerns include "range anxiety" as a result of the perceived limited driving range of electric batteries versus the perceived range needed in daily car use, charging time of batteries, and a lack of available charging stations as compared to gas/diesel fuel stations (Dong et al., 2020; Sovacool & Hirsh, 2009). A study by Hidrue et al. (2011) attempted to estimate consumers' willingness to pay for five key EV attributes: driving range, charging time, fuel cost saving, pollution reduction, and performance. The factors most important to respondents were driving range, fuel cost savings, and charging time. At the same time, their results suggest that battery costs must drop significantly before EVs find a mass market without subsidies.

Previous research examining environmental factors related to EV adoption has focused primarily on fiscal incentives for users (Brand et al., 2013; Gass et al., 2014) and regulation of manufacturer emissions or vehicle efficiency (Walther et al., 2010; Thiel et al., 2014). This research has generally agreed that due to the high-cost differential between EVs and their ICE counterparts, fiscal incentives are required to substantially increase consumer adoption of EV technology. In the next section, we discuss the methodology utilized for this study.

3. RESEARCH METHODOLOGY

To explain the diffusion of innovation within the sustainable automobile sector, this study pursues a descriptive approach, rather than an empirical one, by examining EV sales trends between 2008–2017, supplemented by current research. Longitudinal sales data across countries is required to conduct trend analyses of OEMs' global diffusion of EV technologies. Data were obtained from EVvolumes.com (www.EVvolumes.com), which tracks EV sales across major markets and countries. EVvolumes.com has supplied data to researchers, newspapers, and auto firms. Articles based on its data have appeared in business press, such as *The Wall Street Journal* and leading academic journals. An alternative method of gathering the data would be to contact each OEM to obtain sales by category of EV in each country for each year.

The obtained dataset contains panel data regarding EVs sold in 89 countries from 2008–2017. The EVs are characterized as BEVs, PHEVs, and HEVs. The dataset also contains the identification of the geographic region of the world, the OEM (manufacturer), and the make and model of the EV. The granular nature of the data allowed the authors of this paper to analyze trends from multiple perspectives.

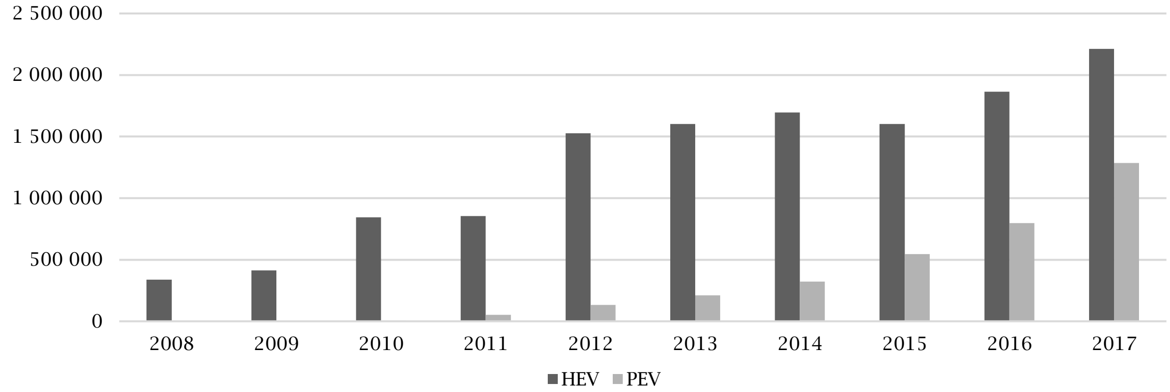
Since this paper focused on understanding broad sales trends, crosstab tables were developed in Excel to assess sales trends over time. A total of 1,710 rows of country-year-OEM-model unit sales data were contained in the dataset. The data was sorted and organized into various categories (e.g., HEV unit sales by OEM, by country, by year; HEV unit sales by country by year, and so forth), one category per spreadsheet page. A second set of spreadsheet pages were created with unit sales converted to percentages of total sales. Each category of sales (units and percentages) was then reviewed for observable trends and relationship to the expected theory. Each trend observation was then discussed among the authors to reach a consensus regarding the trend's inference. The length and complexity of the tables led us to develop graphs to simplify the data for presentation. The volume of entries in the tables and figures, many with zero or otherwise insignificant data, led us to limit the number of entries (sometimes showing only the top 5–13 firms/countries) per table or figure (as noted on each table/figure).

4. RESULTS

4.1. Trend 1: Trends in worldwide HEV and PEV sales

A review of Figure 1 reveals that worldwide HEV sales from 2008–2017 increased from 337,793 units to 2,211,494 units, an annualized growth rate of 23.2%, while PEV sales have grown from 468 units to 1,284,740 units over that same period, an annualized growth rate of 141%. Toyota Prius, launched in 1997, was the first modern HEV, while PEVs were mass-produced beginning in 2010.

Figure 1. Worldwide sales of HEV and PEV by year



These data are thought-provoking from multiple perspectives. For example, why is there such a stark difference in the annual growth rates of sales between HEVs (23.2%) and PEVs (141%)? Has the HEV technology matured (since it debuted in 1997), whereas the PEV technology is in its growth phase? Will HEVs co-exist with PEVs for an extended period, or does this trend indicate that PEV technology will replace HEV as the dominant non-ICE technology? According to Anderson and Tushman (1990), technological discontinuity (innovations that improve the price-to-performance ratio significantly and are a new way of making something or a new fundamental product architecture) leads to a dominant design, which is followed by a period of incremental innovations, which in turn is disrupted again by another technological discontinuity. This may describe the current environment within the SNT of automobiles. Further, these observations were made in the context of worldwide sales. Additional moderating factors, such as the availability of infrastructure, government policies, and the tastes and demands of consumers, vary across countries and may influence these rates (Jaiswal & Zane, 2022). These regional variations might affect the previously thought uniform predictions of the dominant design theory propounded by Anderson and Tushman (1990).

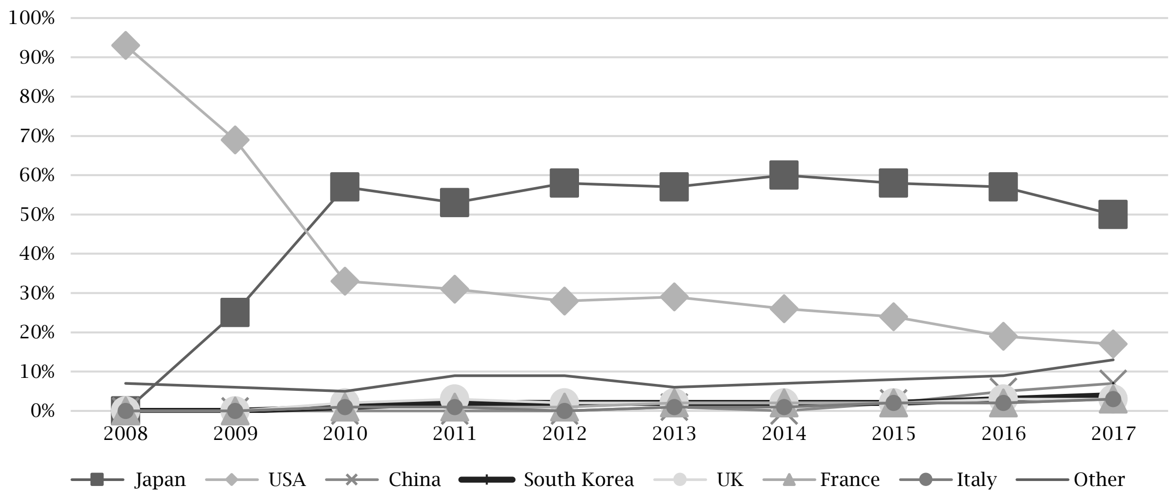
Another question is whether this ramp-up movement from HEV to PEV was a strategic bet by industry leaders. Did TMTs at automobile manufacturers make strategic bets based on the realization that the PEV market had developed to a stage where it was worth ramping up production and sales to take advantage of increased market demand? While R&D departments can develop new technologies, and governments can incentivize markets and industries to increase the speed of diffusion, the private sector's actions ultimately turn an innovation into a mass-consumed product. Many factors could drive auto manufacturers' decisions to dive into the PEV market. For example, they may see PEVs as embracing the future or riding the "sustainability" wave. They may be pursuing PEVs out of fear, believing they did not capitalize on the previous HEV wave and do not want to miss the PEV wave. Alternatively, some firms' capabilities, resources, and activities may better support the adoption of PEV compared to HEV technology.

OEM-level analyses of what motivated individual firms to enter the HEV versus PEV markets could inform about the role of the TMT's perceptions of the environment and availability of competencies in private sector decisions affecting the global diffusion of SNTs. For example, Inkpen (2020) detailed the history of General Motors' (GM) decisions by examining the environmental and competitive factors GM faced over the years. Case studies can provide insight into the decisions of TMTs by highlighting factors faced by firms compared to resultant decisions.

4.2. Trend 2: HEV and PEV adoption — Analysis at the country level

Japan, the USA, and China accounted for 74% of HEV vehicles sold in 2017 (see Figure 2). In 2008, the USA market was dominant in HEV sales with 93%, but by 2017 had ceded that position to Japan (50% market share for Japan vs. 17% for the USA). This raises important questions — how could Japan significantly increase the adoption of HEVs? Was it Japanese government policies (incentives or mandates directed toward manufacturers), decisions by the private auto sector (OEMs such as Toyota and Nissan), or consumer demand that led to Japan becoming a dominant player in HEVs? The role of industry-government partnerships is vital. It could explain the ascendancy of Japan (Pohl & Yarime, 2012) versus countries with similar industry-government partnerships, such as South Korea and Russia, who remain fringe players in HEV.

Figure 2. Country share (percent) of worldwide HEV sales (top markets)



Note: Top seven entries (3% or more).

China registered HEV sales starting in 2013 and soon catapulted over nations such as Germany, France, Sweden, and Norway (7% as of 2017 and growing). State Capitalism (Aligica & Tarko, 2012) could play an important role in adopting mass-scale technologies. It could be a fruitful avenue to explore the differences between China and these other countries regarding HEV policy and resulting OEM decisions. In China, coordination between government and industry was implemented so effectively that the Chinese market quickly became a major force.

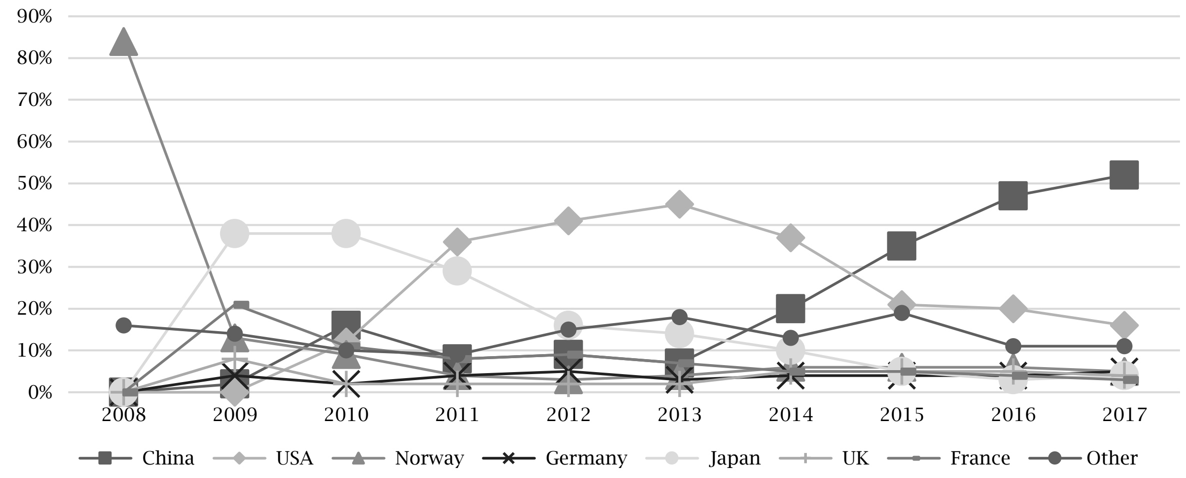
An interesting case study by Ma et al. (2019) discusses the environment in China, including government actions that encouraged local development and consumption of EV technology and the resulting decisions of NIO to ramp up development and production so quickly. While the environment in each country differs, and the resources and competition of firms vary widely, the China HEV case may provide a game plan for policymakers to encourage and support local production by firms. Future studies in other countries could shed light on policies enacted, the decisions made by firms, and ultimately, the economic and environmental outcomes derived.

Another noteworthy observation is that many countries involved with HEVs since 2008 have maintained a small percentage share of sales. Since worldwide sales grew 650% from 2008–2017, it seems that the manufacturers and markets in these countries are neither embracing nor fully opting out of this technology, appearing to be "sitting on the fence". Why would some countries' manufacturers and markets behave this way concerning new technology? Does government policy or demand or supply-side phenomenon drive this behavior? This may be a case where a "real options" perspective, where markets are entered cautiously to study the market and technology and preserve the ability to enter more fully if the market takes off, can explain the behavior of firms within these countries (Bowman & Hurry, 1993; Folta & Miller, 2002).

Taking steps to launch a new product involves a significant commitment of time and resources, resulting in substantial sunk costs. Evidence suggests that delaying predictions derived from real options logic tend to accurately predict what decision-makers do when faced with discretion, uncertainty, and investment irreversibility (Kogut & Kulatilaka, 2001). For example, GM developed an EV in the '90s, but due to uncertain markets, they canceled the entire operation (Neil, 2009). Later, they watched Toyota's success and tried to catch up. The Chevy Volt hybrid was launched in 2010 but has enjoyed only limited market success.

The top four countries by sales for PEVs — China (52%), the USA (16%), Norway (5%), and Germany (5%), accounted for 77% of worldwide sales in 2017 (see Figure 3). Interestingly, as in the HEV market, one country is a clear leader in the number of vehicles sold — China. We observe that Japan, the leader in the HEV market, is not a major player in the PEV market. In contrast, we observe that the USA and China have a significant presence in both HEVs and PEVs. Why do industries in some countries get "locked" but others do not? What characteristics of a country or regional industry lead to such lock-ins, and on the other side, what characteristics of a society, market, or policy, make industries able to straddle and succeed with multiple technologies? Again, we observe a "fence-sitting" approach in almost the same countries that were doing so in the HEV market — mainly Germany, France, the UK, Belgium, and Sweden.

Figure 3. Country share (percent) of worldwide PEV sales (top markets)

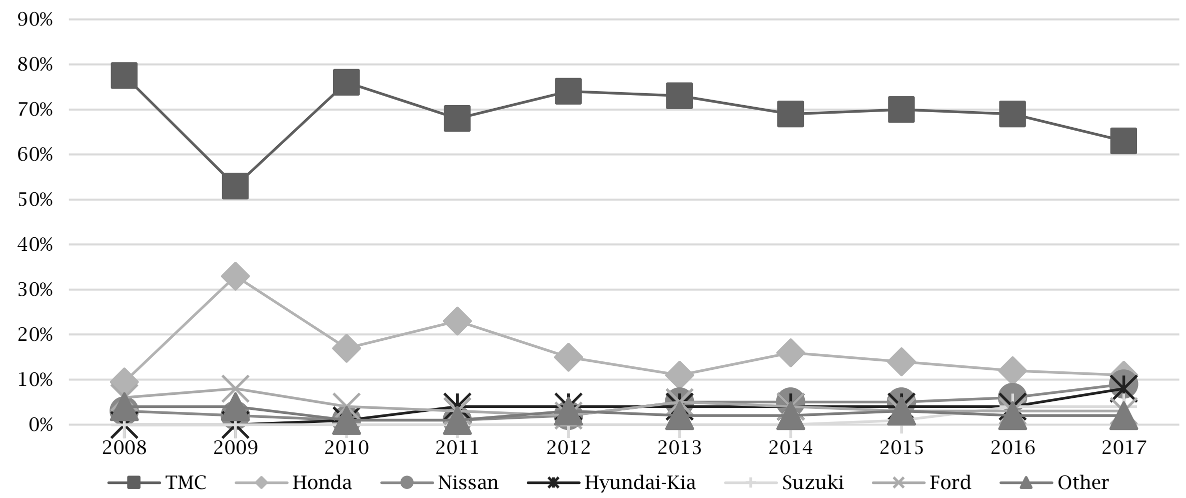


Note: Top seven entries (3% or more).

4.3. Trend 3: HEV and PEV sales — Analysis at the firm level

In the HEV segment over the 2008–2017 period, 18 of 25 OEMs could be termed legacy as they were founded before the HEV/PEV revolution. The HEV industry is highly consolidated with the top six players — Toyota, Honda, Nissan, Hyundai-Kia, Suzuki, and Ford, accounting for 99.08% of worldwide sales in 2017 (see Figure 4). These top OEMs also happen to be legacy OEMs. Toyota (TMC) is a clear leader, with close to 63% of worldwide sales in 2017.

Figure 4. OEM share (percent) of worldwide HEV sales (top OEMs)



Note: Top six entries (3% or more).

Tushman and Anderson (1986) broadly divide technological discontinuities (technological breakthroughs) into — competence-enhancing and competence-destroying. The authors posit that opportunities opened up by competence-enhancing discontinuity will usually be exploited by existing firms in the industry since these firms already possess the competencies to take advantage of the discontinuity. HEV technology uses the ICE as the vehicle's prime mover and is also equipped with a battery backup to avoid excessive burning of fuel. Thus, at a minimum, HEV can be considered a competence-neutral discontinuity if not a competence-enhancing one. Furthering this notion, Suarez et al. (2018) refer to this phenomenon as "The Hybrid Trap." They explain how mature companies often lack the vision and resolution to commit to new technologies, even when markets appear ready to accept them, to explain the decision by some firms to fully commit to HEV technologies while PEV technologies were on the horizon.

We also observe that four of the top five OEMs in the HEV segment are Japanese. It could be valuable to understand what triggered the proclivity of the Japanese OEMs to commit to producing and selling HEVs. At a more micro level, why did Toyota take the lead in HEVs compared to Honda? Was it a strategic decision by Toyota or strategic oversight by Honda, or did Toyota have a history of dabbling with HEV technologies, or could there be other reasons? In their study of the Japanese market, Pohl and Yarime (2012) found that automakers were proactive in taking the lead on HEV development. However, this study is limited to Japan. A broader research question could be whether such models are applicable worldwide. Research could shed light on how companies decide and execute the adoption of new and innovative technologies. It is also important to understand why certain legacy carriers such as GM, Mitsubishi, VW Group, and BMW "sat out" this stage of the evolution of the auto industry. For example, Mitsubishi, the OEM with the longest history in Japan, is not participating in the HEV market to the same extent as other Japanese OEMs. However, they did make a move into the PEV segment, which we will discuss next.

In the PEV segment, over the 2008–2017 period, we find 67 OEMs participating in the industry (see Table 1). Furthermore, there is a healthy mix of legacy and new OEMs. The industry is fragmented, with the top five OEMs — BYD, BAIC, Tesla, BMW, and VW accounting for only 38.55% of the sales. The top-selling OEMs are not legacy, but new OEMs. As of the 1st quarter of 2022, with worldwide PEV sales of 1,997,348, Tesla (15.5%) has taken over as the top seller, followed by BYD (14.3%), SAIC (8.5%), Volkswagen Group (7.8%), and Geely-Volvo (5.5%). When examining only BEVs' worldwide sales of 1.44 million, the leader is Tesla (21.6%), followed by SAIC (10.7%), BYD (10%), Volkswagen Group (6.8%), and Hyundai (5.7%) (Kane, 2022).

Table 1. OEM share (percent) of worldwide PEV sales (top OEMs) — sorted in 2017

OEM	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
BYD	0%	2%	7%	2%	2%	1%	6%	11%	13%	9%
BAIC	0%	0%	0%	0%	0%	1%	2%	3%	6%	8%
Tesla	0%	2%	6%	1%	2%	10%	10%	9%	10%	8%
BMW Group	0%	6%	1%	0%	1%	1%	6%	6%	7%	8%
VW Group	0%	0%	0%	0%	0%	1%	4%	11%	8%	5%
Geely	0%	0%	0%	0%	0%	0%	0%	3%	5%	5%
SAIC	0%	0%	0%	0%	0%	0%	1%	2%	3%	4%
TMC	0%	0%	0%	0%	17%	10%	6%	1%	1%	4%
GM	0%	0%	5%	16%	23%	14%	8%	4%	4%	4%
Nissan	0%	0%	1%	43%	20%	22%	19%	9%	7%	4%
Renault	0%	0%	0%	3%	12%	8%	5%	5%	3%	3%
Hyundai-Kia	0%	0%	0%	0%	0%	0%	1%	2%	2%	3%
Daimler	0%	6%	6%	3%	1%	2%	2%	3%	3%	3%
Zotye	0%	0%	0%	0%	1%	0%	2%	4%	5%	3%
Chery	0%	0%	0%	4%	2%	3%	3%	3%	3%	3%

Note: The table shows those OEMs which registered 3% of global sales in 2017. A total of 67 OEMs were operating in the market between 2008–2017.

An interesting research topic is understanding how new OEMs could reach a preeminent position so quickly. A recent case study examined Tesla, the current EV leader, in a detailed fashion (Van den Steen et al., 2021). This case examines the history, competition, and decisions implemented by Tesla in reaching the top. The question then becomes, can they stay on top? Being first to market does not guarantee long-term advantage; it does, however, provide the opportunity to set standards (Zane et al., 2014). According to Tellis and Golder (1996), pioneers (first to market) had a failure rate of 47%, and they controlled 10% of their respective markets. Early followers had minimal failure rates and controlled three times the market share. While market share initially went to first movers, long-term success was attributed to the vision, managerial persistence, financial commitment, relentless innovation, and leveraging of assets, not merely market entry timing.

Perhaps, with EVs, the automobile manufacturing process is no longer a significant barrier to entry; it has evolved into a commodity process. Conceivably, other aspects, such as knowledge of battery technology, and electric powertrains, will decide who becomes dominant. Tushman and Anderson (1986) posit that competence-destroying discontinuities may create a new product sub-class or a substitute for an existing product. The BEV-based vehicles can be thought of as a new sub-class of autos. Competence-destroying discontinuities are fundamentally different from the dominant technology and hence, require a mastery of new skill sets. The BEV technology utilizes the battery as the main power source and the auto's prime mover; thus, it requires mastery of new technologies such as battery and charge storage. Therefore, the BEV may be considered a competence-destroying discontinuity (Wesseling et al., 2015). Tushman and Anderson (1986) propose that opportunities opened by competence-destroying discontinuities will commonly be exploited by new firms in the industry, reasoning that since these firms are bringing new technology to market, they are not hindered by sunk costs and internal political constraints.

OEMs such as Toyota and Honda obtained a significant market share in HEVs. However, they are not notable players in the PEV segment. Was this a strategic decision, or were they constrained by lack of access to resources, personnel, or technology? Similarly, we find that OEMs such as BMW and VW, which did not participate in the HEV segment, are significant players in the PEV market. It is important to understand how such decisions are made. An interesting case study by Schotter et al. (2019) details Volkswagen's history, governance structure, culture, finances, and evolving strategic plan to convert from almost 100% ICE vehicles to BEVs. VW plans to launch over 30 new BEVs by 2025, investing upwards of $50 billion. A related VW initiative is developing battery technology as a core competency.

4.4. Trend 4: HEV and PEV OEM sales by country

Legacy OEMs in HEV and PEV segments are not truly global. Their sales primarily accrue from four to five countries. For example, Toyota, the largest seller of

HEVs, has sales in Japan (its home base), the USA, China, Italy, the UK, Spain, France, and Germany (refer to Tables 2a–2c). A similar pattern is found for PEVs (refer to Tables 3a–3c). The Chinese PEV OEMs primarily sell in China, although BYD is in the process of opening a manufacturing plant in Mexico.

These results lead to a major question. How do OEMs target countries for the introduction of SNTs? Is it primarily because they have an existing presence in these markets? How much does the population's receptivity (to innovations or "green" technologies) matter, or government incentives (Jaiswal & Zane, 2022)? Secondly, why have Chinese OEMs, which have been ramping up production, remained mostly local until recently? Is it because they are nascent OEMs and hence, lack a beachhead in foreign markets? Or maybe the demand in China is so high that they are at capacity serving the local market?

The problems caused by COVID-19 drove home several points to international businesses. Specifically, critics of global supply chains have called for making the long international supply chains shorter and more regional. And more diversified to help make them more resilient, or less subject to interruption. Politics and geo-political concerns have pushed in this direction as well. While making the entire automotive supply chain based in one country may not be realistic, the automotive industry is making significant changes. Three regional value chains are emerging. One for the Americas, centered on Mexico; a second for Europe, centered on Eastern Europe and Morocco; and a third for Asia, centered on China and Southeast Asia (Peng, 2022). As expected, regional trade agreements also significantly affect these decisions.

It must also be understood that competition and trade policies vary from country to country. For example, In the USA, trade policies are pro-competition and pro-consumer. In the USA, fairness means equal opportunity for incumbents and new entrants. In contrast, Japan is pro-incumbent and pro-producer. Their position is that incumbents, who have invested in the industry for a long time, deserve to be protected from new entrants, so new entrants in Japan do not receive equal treatment. The USA wants a dynamic market, while the Japanese want an orderly market (Peng, 2022). Along with tariffs, trade policies, and restrictions on foreign direct investment, government policies significantly affect which countries firms enter and how successful they become.

Table 2a. HEV units sold by TMC worldwide — Sorted in 2017

Country	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
Japan		8,494	391,993	315,782	670,704	675,040	679,270	631,992	679,327	631,004
USA	241,405	188,846	189,181	178,587	314,474	331,708	296,755	264,339	243,940	203,268
China	899	271	1	4	3,902	6,065	7,073	30,999	83,845	126,126
UK			10,545	15,369	17,529	24,089	32,565	38,942	44,292	55,578
Italy			3,008	3,810	4,731	13,371	19,434	24,528	35,753	54,935
France			3,960	8,724	14,844	20,523	22,489	26,224	40,150	54,278
Spain			4,684	8,739	8,942	8,836	11,669	7,572	24,613	44,869
Germany	5,091	5,475	4,541	4,221	10,231	15,218	11,714	12,825	29,792	41,740
Canada	4,458	4,879	6,739	6,539	17,412	14,168	13,421	12,214	11,473	25,384
South Korea			1,974	3,532	6,000	5,622	7,516	8,860	14,975	18,900

Note: TMC recorded sales in 83 countries in the 2008–2017 period, top ten shown (for 2017).

Table 2b. HEV units sold by Honda worldwide — Sorted in 2017

Country	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
Japan		93,283	87,492	133,188	184,091	145,596	239,847	201,890	204,224	196,908
USA	31,297	35,691	33,547	31,582	18,166	18,050	26,574	20,755	12,955	25,461
China							53	152	2,641	16,242
South Korea			183	303	263	116	3		2	2,257
UK			6,153	9,064	5,826	2,937	1,330	488	13	93

Note: Honda recorded sales in 36 countries in the 2008–2017 period, top five shown (for 2017).

Table 2c. HEV units sold by Hyundai-Kia worldwide — Sorted in 2017

Country	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
South Korea			6,186	16,167	29,717	22,054	27,820	28,973	44,202	60,689
USA				19,673	30,838	35,680	34,828	31,400	25,103	53,877
Israel									232	11,074
UK									1,727	8,360
Spain						33	12		1,016	6,773

Note: Hyundai-Kia recorded sales in 48 countries in the 2008–2017 period, top five shown (for 2017).

Table 3a. PEV units sold by BYD worldwide — Sorted in 2017

Country	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
China		48	480	1,014	2,891	2,691	18,439	61,732	102,465	113,974
Singapore						0	0	0	0	101
Ecuador									0	30
Uruguay						0	0	0	0	26
Colombia						20	23	0	1	22

Note: BYD recorded sales in 18 countries in the 2008–2017 period, top five shown (for 2017).

Table 3b. PEV units sold by BAIC worldwide

Country	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
China					644	1,484	5,234	17,060	46,481	104,485

Note: BAIC recorded sales only in China in the 2008–2017 period.

Table 3c. PEV units sold by BMW worldwide — Sorted in 2017

Country	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
USA					673	0	6,647	14,198	16,107	21,208
UK		40			160	94	1,681	3,132	8,541	15,274
Germany		68	1			559	2,631	3,109	5,286	11,042
Norway						51	2,059	2,547	6,584	9,738
Malaysia						0	0	0	0	7,713
Belgium						32	409	603	2,983	5,428
Japan						0	831	1,260	355	5,008
China						35	142	1,116	2,415	4,910
France			50		10	84	589	975	2,904	4,308
Sweden						11	216	476	1,630	2,782

Note: BMW recorded sales in 70 countries in the 2008–2017 period, top ten shown (for 2017).

4.5. OEMs in PHEV and BEV markets

The BEV industry is relatively fragmented (see Table 4); the top five OEMs account for 43% of worldwide sales with no clear dominant leader. A few new OEMs, such as BYD and BAIC, are in the top five sellers.

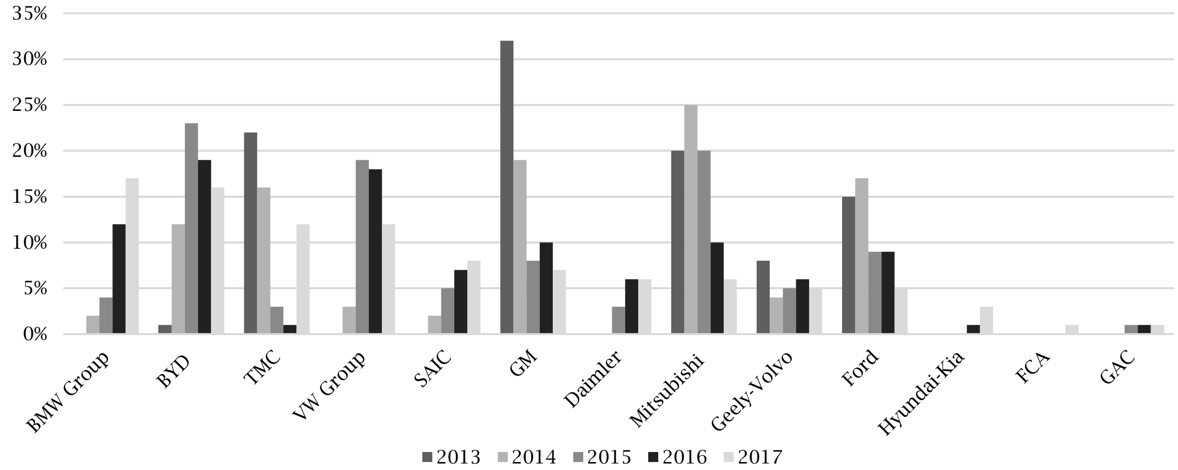
Table 4. OEM share (percent) of worldwide BEV sales — Sorted in 2017

OEM	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
BAIC	0%	0%	0%	0%	1%	1%	3%	5%	9%	12%
Tesla	0%	2%	6%	1%	4%	18%	16%	15%	15%	12%
Geely	0%	0%	0%	0%	0%	0%	1%	5%	7%	8%
Nissan	0%	0%	1%	52%	36%	39%	31%	15%	11%	6%
BYD	0%	0%	1%	1%	2%	1%	2%	4%	10%	5%
Renault	0%	0%	0%	4%	22%	15%	9%	8%	5%	4%
Zotye	0%	0%	0%	0%	1%	0%	4%	7%	7%	4%
Chery	0%	0%	0%	5%	4%	5%	4%	4%	3%	4%
BMW Group	0%	6%	1%	0%	1%	1%	8%	8%	5%	4%
JAC	0%	0%	10%	2%	3%	2%	1%	3%	4%	4%
JMC	0%	0%	0%	0%	0%	0%	0%	2%	3%	3%
Changan	0%	0%	0%	0%	0%	0%	0%	0%	1%	3%
Hyundai-Kia	0%	0%	0%	0%	1%	0%	1%	3%	2%	3%
GM	0%	0%	0%	0%	0%	1%	1%	1%	1%	3%
SAIC	0%	0%	0%	0%	0%	0%	0%	0%	0%	3%
Dongfeng	0%	0%	0%	0%	0%	0%	0%	1%	1%	2%
VW Group	0%	0%	0%	0%	0%	1%	4%	6%	3%	2%
Kandi	0%	0%	0%	0%	0%	0%	6%	4%	2%	2%
Hawtai	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
Daimler	0%	6%	7%	3%	2%	4%	3%	3%	1%	1%
Lifan	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%
PSA	0%	2%	5%	9%	9%	1%	1%	1%	1%	1%
FAW	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
FCA	0%	1%	0%	0%	0%	1%	1%	2%	1%	1%

Note: Top 23 OEMs (1% or more in 2017).

Figure 5 shows that the PHEV industry is slightly consolidated, with the top five players accounting for 66% of sales. It is interesting to note that legacy OEMs are leaders in PHEVs (i.e., BMW, Toyota, and VW Group in the top five); however, only one legacy OEM (Nissan) is a leader in the BEVs (see Table 4). Research may uncover whether this is a strategic move by the legacy OEMs or whether they are constrained by the resources, capabilities, personnel, and technology required to enter the BEV market. If BEV becomes a dominant segment in the auto market, it might lead to the unseating of several legacy OEMs.

Figure 5. OEM share (percent) of worldwide PHEV sales (top OEMs) — Sorted in 2017



Note: Top 13 OEMs (1% or more in 2017).

This situation is reminiscent of the computer industry and the changing of the guard of major players as the industry evolved. During this evolution, we saw business computers produced by IBM, the 'Bunch' (Burrows, Univac Rand, NCR, Control Data, Honeywell), and a few others during the 1950s, but by 1960, IBM came to dominate with the introduction of the model 1401. Then, firms new to the industry, like Digital Equipment Corp. (DEC), led the charge into the new minicomputer market; these new firms seized and held a significant market share. This situation played out again in the Personal Computer (PC) market. New players included Apple, Commodore, Tandy, and Compaq. Established mainframe and minicomputer producers were slow to see the new market and users' needs in that market (Malerba et al. 1999).

Firms often have difficulty when they try to do significantly new things. Tushman and Anderson (1986) and Henderson and Clark (1990) have documented the difficulty firms often have in coping when the technologies underlying their products change significantly. Quite often, extant firms cannot switch over rapidly enough to counter the efforts of new firms using the "new" technology. Rosenbloom and Christensen (1994) highlighted similar difficulties that extant firms had in recognizing new markets when they opened up.

5. DISCUSSION

We reviewed worldwide sales data of EV technologies from 89 countries covering 2008–2017. The data were supplemented with recent research and articles. Using this combined data, we observed many trends, raised practical and theoretical questions, and proposed theories and research projects to answer these questions.

The data indicate that individual sub-categories of EV vehicles are developing at different rates and that stark differences exist among countries and manufacturers. These observations suggest that not all sub-categories of EVs are equal in the minds of consumers, manufacturers, and governments. The automotive industry, which includes manufacturing, selling, and servicing automobiles and trucks, employs many, accounts for a significant percentage of gross domestic product (GDP) in many countries, and generates substantial revenues for industry and government. Changes in the automotive industry attract the interest of many in both the private and public sectors as they attempt to influence outcomes to favor their interests.

From a theoretical perspective, the trends witnessed in this research support many of the tenets of TMT theory. Strategies chosen by firms are affected by perceptions of the environment (Droege & Marvel, 2009; Zane & Kline, 2017) as well as TMT characteristics and their competitive positions concerning resources and markets, and their goals and vision for the firm (Hambrick & Mason, 1984; Hambrick et al., 1996).

In addition, real options theory may explain some of the fence-sitting by particular OEMs. According to Gersick (1994), whether actions can or should be initiated is contingent on clarifying conditions or signals emanating from the environment. Business leaders (in the face of uncertainty) tend to preserve strategic flexibility (Hayes & Garvin, 1982) to maximize the expected return from their investment. One method of maintaining flexibility is to hold options open to reduce potential losses as much as possible (Bowman & Hurry, 1993) while allowing for upside. Hence, some firms dipped their toe in the EV water but did not fully commit.

The declaration of new EU rules and regulations mandating that no new ICE vehicles can be sold after 2035, forces all parties involved in the automotive industry to work in earnest to develop EV-related technology. However, each OEM may choose a different path related to its capabilities and vision. According to Bohnsack et al. (2020), first movers in EVs usually position their involvement as part of their corporate social responsibility and sustainable innovation efforts. In contrast, followers leaned more towards seeing EVs as a means to achieving competitive advantage by proceeding or avoiding competitive disadvantages if they missed the opportunity.

Why industries in some countries appear locked into one technology may be a matter of national infrastructure or culture. HEV vehicles utilize a country's existing service stations for refueling and require little change in consumer behavior. Conversely, PEV vehicles require a national network of charging stations. In addition, consumers may need to install charging outlets in their homes, an improvement that may not be easily accomplished in some neighborhoods, especially those with a large volume of apartments or multi-level condominiums, or a maxed-out power grid. A society with high uncertainty avoidance may be reluctant to make the move to PEV technology as it presents several uncertainties (Jaiswal & Zane, 2022). For example, when using PEVs, it may be hard to predict the actual miles an automobile may travel since inaccuracies may creep up in predicting potential travel ranges as the battery discharges. Similarly, electric charge stations are not as common as gas stations, thus leading to concerns of range anxiety.

6. CONCLUSION

Understanding how SNT is developed and diffused globally is important to strategy and entrepreneurship education and business leaders. This research contributes to strategy and entrepreneurship education, as well as, theory by informing scholars and practitioners about the causes and effects of variation in technology diffusion across world markets from an OEM perspective.

The issues raised by the COVID-19 pandemic led to massive upheaval in global supply chains to make them shorter, more regional, and more resilient. Politics, regional trade agreements, and geo-political concerns have pushed in this direction as well. These factors, as well as incentives for OEMs and consumers, influence TMTs' decisions on the choice of technology and markets to pursue.

From a policy perspective, research informs us on how to encourage the market to purchase EVs in general (Chandra et al., 2010), and that policy can motivate manufacturers to produce EVs. Lessons from this research show that government policy can work to motivate consumers to purchase PEV technologies even though it requires more investment and induces uncertainty by OEMs and consumers. However, it is vital to develop a holistic understanding of the reasons that lead to the uneven diffusion of EV technology across countries. We propose expanding this research stream to include additional independent variables representing the formal (laws, regulations, and rules) and informal (cultures, ethics, and norms) institutions of countries or regions and to observe the effects over time.

Regarding theory, further research on decisions by OEMs to invest in or bypass a technology should be added to the debate where government intervention and incentives have been deeply studied. From a geographic standpoint, an expansion of scope so that multiple markets are analyzed in the same study is warranted since the above-mentioned factors may interact in different ways to lead to similar or different results. Including multiple variables and employing data from multiple countries or regions will enhance the generalizability of the results.

Future research in this area might look to develop empirical results based on the relationship between characteristics of TMTs of OEMs or regional-level characteristics of the countries in which they are located and diffusion rates of EV or other SNTs. Based on the data available, this study could not pursue this line of research.

This study focused on multiple versions of sustainable technology (EVs) produced and sold by OEMs and its diffusion across multiple countries. Future studies could expand the scope to other sustainable technologies. Perhaps a future study could combine culture and governance to determine the independent versus the combined effects. As mentioned above, the recent coronavirus pandemic led to systemic changes in global supply chains, which can affect diffusion. Thus, studying the coronavirus pandemic's impact on the cross-country diffusion of technologies could be worthwhile. Finally, future studies could replicate the current study simultaneously with other SNTs diffusing internationally to see if similar or different trends appear.

This study, like any other, has limitations. Although the data covered 89 countries between 2008–2017 and was supplemented by current research and articles, there was little data for many countries and OEMs due to the early nature of the technology and decision by OEMs regarding their choice of EV technology, which markets to enter, and timing of entry. In addition, inferences were made by the authors based on their interpretation of government policies and theories from strategic management and technology, in combination with numerical sales trends. While formal and informal institutions such as trade and competitive policies and incentives for consumers and manufacturers were discussed, they could not be empirically tied to the results. Finally, the variability of exchange rates, along with national rates of inflation and wealth, would be expected to impact the decisions of OEMs to enter particular markets.

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