ABSTRACT

Title of Dissertation:	ESSAYS ON MARKET TRANSFORMATION AND ENTREPRENEURIAL STRATEGIES: EVIDENCE FROM THE LITHIUM-ION BATTERY INDUSTRY
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This dissertation uses an Inference to the Best Explanation approach for two essays on the evolution of the Lithium-ion battery industry (1991—2023).

In the first essay, I consider an industry-level perspective and use quantitative and qualitative data to document the emergence and evolution of the Li-ion battery industry. The observations of multiple waves of new firm entry and more than one instance of sales takeoff highlight an empirical puzzle. Thus, I propose a conceptual framework of *Market transformation (MT)* that is qualitatively related to but distinct from the traditional frameworks of Industry Emergence and Disruption. By comparing the predictions of the Industry Emergence and Disruption approaches with those of the

proposed MT framework, I argue that the proposed framework provides a better explanation for the observed evolutionary trajectory of the Li-ion battery industry.

In the second essay, I consider the strategic choices of application markets and entrepreneurial strategies from a firm-level perspective to examine how did start-ups choose their entrepreneurial entry strategy when application markets are characterized by different sizes and levels of uncertainty. Assembling a dataset of 151 US-based battery start-ups founded in the Li-ion battery industry, I report on the start-ups' choices of application markets and entrepreneurial strategies at entry across three distinct periods in the evolution of the Li-ion battery industry. The observation of only 16% of start-ups choosing a specialization-in-generality strategy while 84% of start-ups choosing alternative strategies during a period of increasing uncertainty (2006—2012) highlights an empirical puzzle. Thus, looking across the multi-decade history of the Li-ion battery industry, the uncertainty triggered by the successful commercialization of consumer electric vehicles (i.e., industry demand shock of the Tesla Roadster) spurred start-ups to enter with different strategic bets; it also triggered investors to support those bets. By elaborating and evaluating the list of possible explanations, I infer that the increasing levels of uncertainty associated with each application market generated *uncertainty profiles* that start-ups selected based on the preferences and beliefs of their entrepreneurs or their investors about the nature of uncertainty, resulting in different *strategic bets*, as the best explanation.

ESSAYS ON MARKET TRANSFORMATION AND ENTREPRENEURIAL STRATEGIES: EVIDENCE FROM THE LITHIUM-ION BATTERY INDUSTRY

by

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List of Abbreviations

BM	Business Model
BEV	Battery Electric Vehicle
CARB	California Air Resources Board
CE	Consumer Electronics
EV	Electric Vehicle
GPT	General-Purpose Technology
GWh	Gigawatt-hours
HEV	Hybrid Electric Vehicle
IBE	Inference to the Best Explanation
IE	Industry Emergence
kWh	Kilowatt-hour
Li-ion	Lithium-ion
MT	Market Transformation
MWh	Megawatt-hour
NiCd	Nickel-Cadmium
NiMH	Nickel-Metal Hydride
PHEV	Plug-in Hybrid Electric Vehicle
SBIR/STTR	Small Business Innovation Research & Small Business Technology Transfer
TRL	Technology Readiness Level
VC	Venture Capitalist
ZEVs	Zero-emission Electric Vehicles

CHAPTER 1: INTRODUCTION

This dissertation consists of two studies on the evolution of the Lithium-ion (Li-ion) battery industry. In each study, I follow an *Inference to the Best Explanation (IBE)* approach to arrive at the "best" explanation to an observed empirical puzzle (Goldfarb, Kirsch, King, Pillai, & Starr, 2022). The structure and approach that I follow in this dissertation were guided and informed by my encounter with the context. During the exploration process, I realized that I was unable to generate ex-ante testable hypotheses in an industry context that was novel, dynamic, and economically important. As a result, I opted early on to embrace a deep-dive approach informed by the IBE perspective whereby I seek questions, not hypotheses, and my answers take the form of explanations to an observed empirical puzzle to motivate a theory that can be applied to other contexts. In such, after developing an expansive contextual knowledge, I identified an empirical puzzle when the contextual observation was inconsistent with the predictions of some prior theory in strategy research that would explain the observed patterns at the industry- and firm-level. From the theoretically-informed puzzle, as my point of departure, I engaged in an iterative process between the context and theory to develop the "lot" of possible explanations. Through such an iterative process, I was able to construct narrow findings to adjudicate between possible explanations to infer the "best" explanation for the observed empirical puzzle.

To set the stage for both studies, I briefly describe the history of the Li-ion battery in terms of its invention and initial commercialization, and then present some basic data about the commercial development process for Li-ion batteries, which is consequential for the world economy.

The scientific discovery of Li-ion battery technology was first demonstrated in the 1970s by a group of scientists in the research group at the global energy giant Exxon. Later, the Li-ion battery was first commercialized in 1991 by Sony Corporation for its camcorder product, and the commercial development of the industry has been ongoing ever since. Initially, the demand for Li-ion batteries was primarily driven by a growing demand in the consumer electronics market (e.g., camcorders, laptops, cell phones). Over time the adoption of Li-ion batteries has increased across multiple application markets. More recently, the demand for Li-ion batteries has been largely driven by the electric vehicle market. However, the fact that it took 15 years until the Li-ion battery technology was first commercialized in a consumer electric vehicle highlights that the technology was not born "general-purpose." Rather, it required entrepreneurial actions by heterogeneous actors and firms to further develop the technology for different application markets. By the mid-2000s, entrepreneurial actions by serial entrepreneurs and technology pioneers led to the commercialization of the first consumer electric vehicle (i.e., Tesla Roadster) using laptop Li-ion batteries. Table 1-1 provides a basic timeline of notable events during the emergence and evolution of the Li-ion battery industry, including key actors, companies, and the development of potential application markets.

[Table 1-1 about here]

The global market size for Li-ion batteries was about $422 million in 1995, $3 billion in 2000, $5.14 billion in 2007 (see Figure 1-1a), and it is currently in a growth stage (as illustrated in Figure 1-1b). Many innovative efforts by actors and firms have contributed to the sharp decline (by about 97%) in the price of Li-ion batteries since its commercial introduction (Ziegler & Trancik, 2021; see Figure 1-2). In recent years, the potential market for Li-ion battery technology has boomed. By 2022, the global market for Li-ion batteries has grown to an estimated $48.19 billion and is projected to grow to $182.53 billion by 2030 (Bloomberg, 2022, Jun 7). In fact, the global Li-ion battery capacity (in gigawatt-hours, GWh) is expected to grow by a factor of five to 10 times in the next decade (Wood Mackenzie, 2022).

[Figure 1-1a & b about here]

[Figure 1-2 about here]

The importance of developing the Li-ion battery industry has expanded beyond the consumer electronics market. Today, the Li-ion battery industry is a critical part of industrial competition between global powers, shapes the development of commodity markets around the world, plays a key role in decarbonizing the global transportation and energy sectors, influences the politics of every country where automobiles are manufactured, and even impacts the economies of oil-producing countries. Apart from developments in Artificial Intelligence (AI), few technologies today have broader import for the future than the fate of the Li-ion battery.

With this background in mind, and because understanding how actors and firms (re-)configure industry knowledge and beliefs in the face of uncertainty is fundamental to research in Strategic Management (Gort & Klepper, 1982; Kirsch, Moeen, & Wadhwani, 2014; Goldfarb & Kirsch, 2019; Pontikes & Rindova, 2020; Moeen, Agarwal, & Shah, 2020; Furr & Eisenhardt, 2021), this dissertation examines the evolution of the Li-ion battery industry and how uncertainty interacts with firms' choices of entrepreneurial strategies. In this context, I decompose uncertainty into different levels and dimensions that can vary based on the evolutionary stage of the industry, market, or technology (Goldfarb & Kirsch, 2019; Moeen et al., 2020; Kapoor & Klueter, 2021).

The first study (Chapter 2) adopts an industry-level perspective and uses quantitative and qualitative data to document the emergence and evolution of the Li-ion battery industry. I document multiple waves of new firm entry and more than one instance of sales takeoff (i.e., "hockey-stick" growth). This finding highlights an empirical puzzle: prior research on industry evolution would have predicted declining rates of new firm entry (i.e., shakeout or consolidation) amid industry sales growth and a single instance of sales takeoff (Gort & Klepper, 1982; Moeen et al., 2020). By comparing the predictions of the *Industry Emergence (IE)* and *Disruption* approaches with those of the proposed *Market Transformation (MT)* framework, I infer that the MT framework provides a better explanation for the observed evolutionary trajectory of the Li-ion battery industry. In addition, when the application of Li-ion battery technology expanded to the electric vehicle market, actors and firms experienced a critical period of *increasing uncertainty* that was *problematic* and would have been unexplained following the IE and Disruption frameworks. Industry trajectories and the nature of uncertainty associated with the evolution of the Li-ion battery industry *did not follow a smooth linear trend* as predicted by the IE approach, *nor a discontinuous trend* as predicted by the Disruption approach. The analysis revealed several boundary conditions in using the IE and Disruption approaches to explain the observed evolutionary trajectory of the Li-ion battery industry. Overall, the findings highlight the possibility of MT as a related but distinct framework (i.e., *hybrid:* neither linear nor discontinuous) for examining the emergence and evolution of this industry. From this context, I suggest that the MT framework may broaden the lens of the IE approach when accounting for the emergence of multiple application markets for general-purpose technologies (GPTs) (Bresnahan & Trajtenberg, 1995; Bresnahan & Gambardella, 1998; Teece, 2018; Conti, Gambardella, & Novelli, 2019; Kapoor & Teece, 2021; Goldfarb, Taska, & Teodoridis, 2023).

In the second study (Chapter 3), I explore how did start-ups choose their entrepreneurial entry strategy when application markets were characterized by different sizes and levels of uncertainty? In so doing, I identified an empirical puzzle by considering the strategic choice of the application market facing an entrepreneurial firm. Using a dataset of 151 US-based battery start-ups founded in the Li-ion battery industry, I report on the start-ups' choices of application markets and entrepreneurial strategies at entry across three distinct periods in the evolution of the Li-ion battery industry identified in Chapter 2. In each period, the potential application markets fundamentally differed in terms of size, scale of batteries required per product, and levels of uncertainty. During the critical period of *increasing uncertainty (2006-2012)*, I observed that only 16% of start-ups choose a specialization-in-generality strategy; that is, only 16% invested in developing general upstream resources and trying to trade them in downstream markets, rather than directly entering downstream markets, while 84% of start-ups pursued alternative strategies (in effect, focusing on a particular market segment). This highlights an empirical puzzle: prior research on the micro-foundations of GPTs (using data from the laser industry) hypothesized that firms specialize-in-generality when they lack downstream assets and/or face a broader application market demand (Conti et al., 2019). However, looking across the multi-decade history of the Li-ion battery industry, the uncertainty triggered by the successful commercialization of consumer electric vehicles (i.e., industry demand shock of the Tesla Roadster) spurred start-ups to enter with different strategic bets; it also triggered investors to support those bets. By elaborating and evaluating the list of possible explanations (i.e., the “lot”), I arrive at the best explanation: infer the increasing level of uncertainty associated with each application market generated *uncertainty profiles* that start-ups selected based on the preferences and beliefs of their entrepreneurs or their investors about the nature of those uncertainties, resulting in different *strategic bets*.

Together, this dissertation contributes to research in Strategic Management by shedding light on (a) how a *Market Transformation framework* allows to systematically examine the evolution of the industry that expands into different application markets and (b) how *uncertainty* interacts with firms' choices of entrepreneurial strategies.

Table 1-1 Timeline of notable events in the evolution of the Li-ion battery industry

Incubation: Energy Crisis, scientists, & scientific discoveries	
1976	Chemist Stanley Whittingham discovered the concept of intercalation electrodes and demonstrated the first Li-ion battery with lithium metal anode and titanium sulfide (TiS) cathode.
1980	Physicist John Goodenough discovered the lithium-cobalt-oxide (LCO) cathode.
1985	Chemist Akira Yoshino patented a Li-ion battery with LCO cathode and a petroleum coke (carbon-rich) anode.
Commercialization & sales takeoff in the consumer electronics market	
1991	Sony Corporation commercialized the first Li-ion battery (using LCO cathode and coke anode) in their camcorder (TR1 8mm).
1991	US Advanced Battery Consortium (USABC) was formed as a cooperative venture between industry and government – major partners included Chrysler, Ford, GM, Electric Power Research Institute (EPRI), and the Department of Energy (DOE) – with the goal to develop and fund electrochemical energy storage technologies that will support the commercialization of electric vehicles.
1992	Asahi Kasei and Toshiba created a partnership (A&T Battery Co.) to produce Li-ion batteries for consumer electronics.
1993	Toshiba commercialized the first laptop (Portege T3400CT) with Li-ion battery.
1994	Motorola commercialized the first cellphone (MicroTac Elite) with Li-ion battery.
1996	John Goodenough, Akshaya Padhi and coworkers discovered a new cathode electrode for Li-ion battery technology – Lithium iron phosphate (LFP).
1997	GM introduced EV1 – first modern mass-produced electric car – using lead acid battery technology.
1997	Toyota introduced its first-generation Prius hybrid electric vehicle.
1997	Most Li-ion battery cell manufacturers shifted to graphite (i.e., soft carbon material) as the anode to attain a flatter discharge curve.
1997	Nissan introduced the first retrofitted electric vehicle – Nissan Altra between 1997 and 2001 – with Li-ion battery technology by Sony (based on LCO cathode).
2001	Christopher Johnson, Michael Thackeray, Khalil Amine, and Jaekook Kim (researchers at Argonne National Laboratories) patented a new cathode electrode for Li-ion battery technology – Nickel, Manganese and Cobalt (NMC).
2001	First appearance of Nickel-Cobalt-Aluminum (NCA) cathode (became a popular cathode used by Panasonic for Tesla's electric vehicles).
2001	US battery start-up A123 Systems introduced a Li-ion battery technology with nanosized LFP cathodes.
2003	Traditional automakers (i.e., GM, Ford, Honda, and Toyota) halted their production of zero-emission electric vehicles (ZEVs) and discarded their leased and commercialized fleets off the market.
2003	Toyota introduced its second-generation Prius hybrid electric vehicle with nickel-metal hydride (NiMH) battery technology.
2003	Tesla Motors was founded by serial entrepreneurs: Martin Eberhard and Marc Tarpenning.
New application market: Electric vehicles	
2006	US carmaker start-up Tesla Motors unveiled its first commercial electric vehicle – Tesla Roadster – using 6,831 laptop Li-ion battery cells.
2006	Largest safety recall in the consumer electronics market from Li-ion battery failure.
2007	Sanyo supplied battery cells for the Tesla Roadster.

2007 Apple commercialized a smartphone (iPhone) with Li-ion battery.
2008 Mercedes introduced their first hybrid vehicle (S400 BlueHybrid) with Li-ion battery.
2008 Energy Improvement and Extension Act granted tax credits for new qualified plug-in electric vehicles.
2009 The American Recovery and Reinvestment Act (ARRA) and American Clean Energy and Security Act (ACES) were aimed to support the development of next-generation batteries, electric vehicles, smart grid technology and infrastructure (included $2 billion in grants for manufacturing advanced batteries and components).
2009 US battery start-up A123 Systems had the biggest IPO of 2009.
2009 Nissan unveiled the Nissan Leaf using Li-ion batteries.
2009 Toyota introduced the third-generation Prius Plug-In Hybrid vehicle using Li-ion batteries.
2010 Tesla Motors went public.
2011 Panasonic signed an agreement with Tesla to supply Li-ion battery cells.
2011 GM introduced its first-generation plug-in hybrid vehicle – Chevrolet Volt – using Li-ion batteries that were supplied by LG Chem.
2011 Amperex Technology Limited (ATL) spun-off Contemporary Amperex Technology Limited (CATL) to mass-produce Li-ion batteries for the electric vehicle market.

Market growth & sales takeoff in the electric vehicle market

2012 Tesla Motors commercialized its second electric vehicle (Model S) using 7,104 Li-ion battery cells.
2012 US battery start-up A123 Systems filed for bankruptcy.
2013 Boeing grounded its fleet of the 787 Dreamliner aircraft due to electrical system problems from its Li-ion battery technology supplied by GS Yuasa.
2014 Tesla and Panasonic signed an agreement to build a large-scale Li-ion battery manufacturing plant (GigaFactory) in the US for Tesla's electric vehicles and its stationary storage technology.
2015 Tesla announced the Powerwall which is a rechargeable Li-ion battery technology designed to store energy at the residential-level.
2016 Samsung recalled approximately 2.5 million Galaxy Note 7 phones due to fires caused by Li-ion battery failure.
2016 The electric vehicle market (i.e., hybrid electric vehicles, plug-in electric vehicles, electric buses) accounts for almost 43% of Li-ion battery demand.
2017 Chrysler introduced its first hybrid Minivan (Pacifica) using Li-ion batteries.
2022 The electric vehicle market (e.g., hybrid electric vehicles, plug-in electric vehicles, electric buses) accounts for almost 80% of Li-ion battery demand.

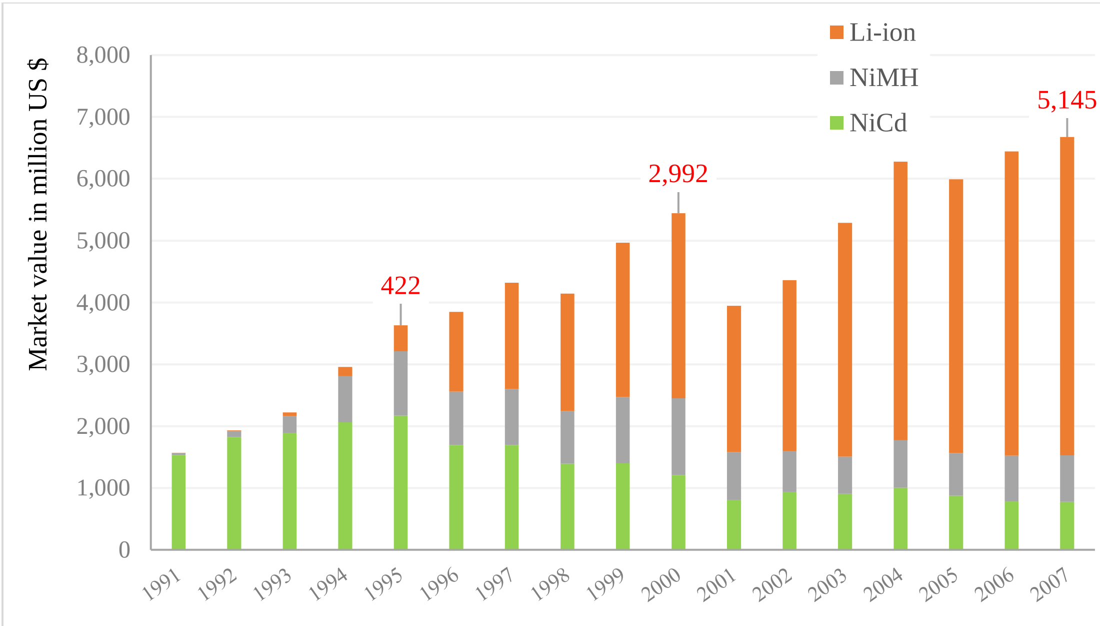

Figure 1-1a Global market value of rechargeable batteries, by chemistry, measured in millions of US dollars (1991—2007). *Source:* Takeshita (2007)

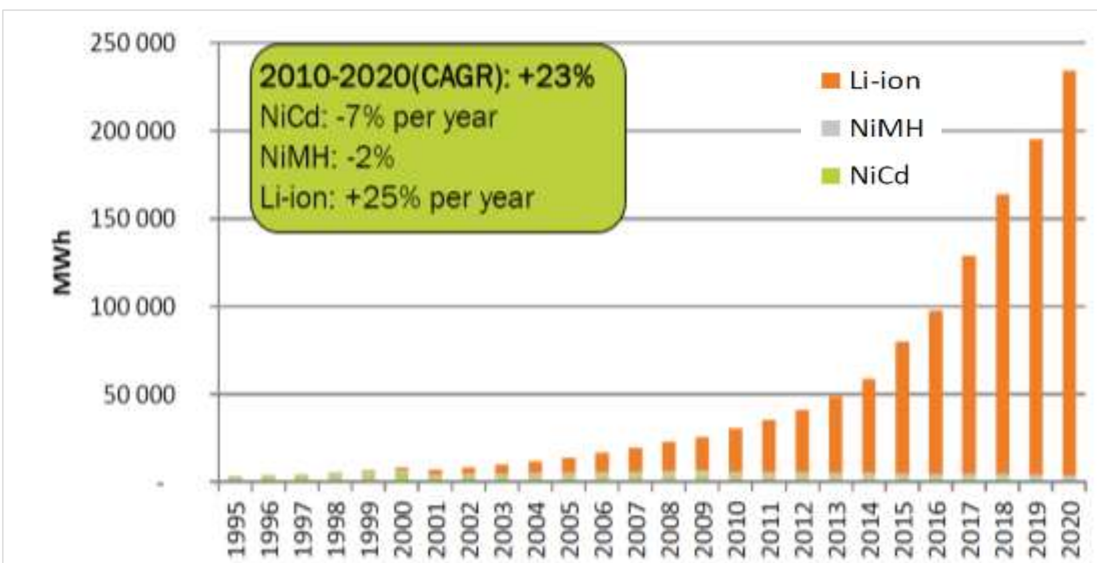

Figure 1-1b Global market demand for rechargeable batteries, by chemistry, measured in MWh (1995—2020). *Source:* Sanders (2021)

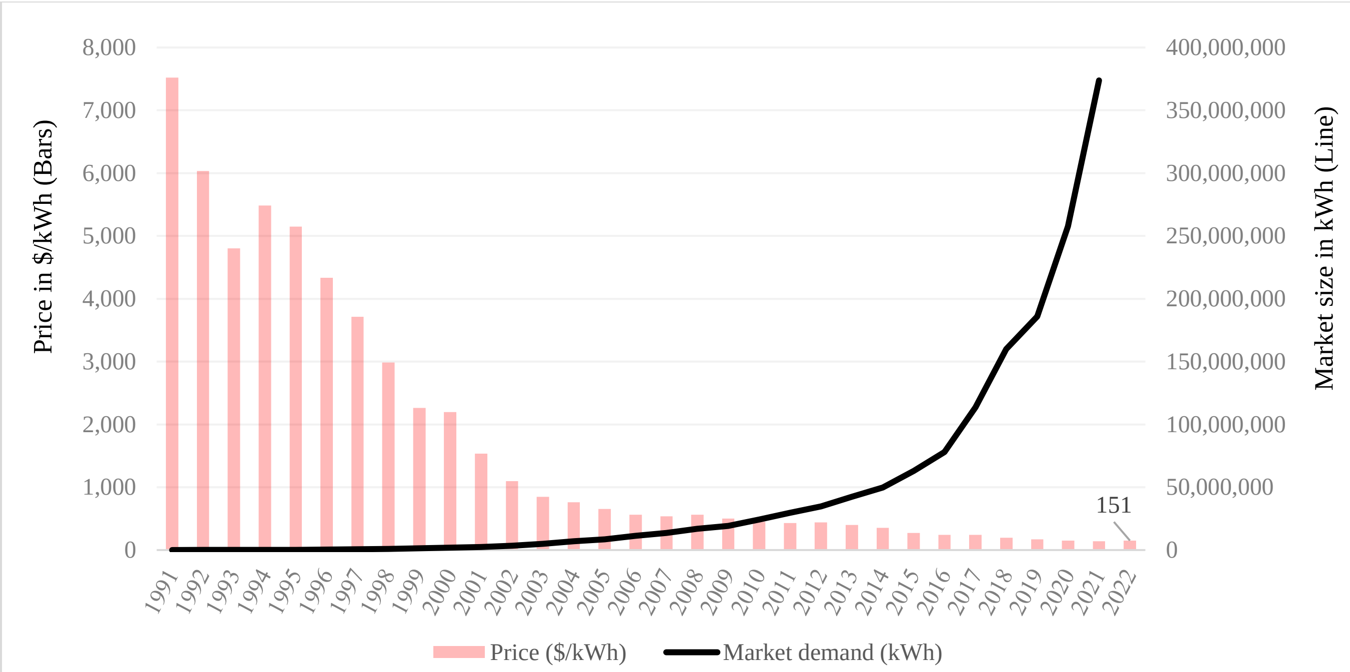

Figure 1-2 Observed price ($/kWh) and demand (kWh) for Li-ion batteries between 1991 and 2016 comes from Ziegler & Trancik (2021). Observed price and demand (kWh) for Li-ion batteries between 2017 and 2022 comes from Stringer & Rathi (2020); Stringer & Park (2021); BloombergNEF (2022, December 6).

CHAPTER 2: ESSAY 1

RESURFACING UNCERTAINTY: MARKET TRANSFORMATION IN THE EVOLUTION OF THE LITHIUM-ION BATTERY INDUSTRY

1. INTRODUCTION

The Li-ion battery was commercialized more than 30 years ago. Over time, the application of the Li-ion battery technology expanded from its initial use in consumer electronics (e.g., camcorders, laptops, cell phones) to a range of other potential applications, including automotive (e.g., hybrid electric vehicles and plug-in electric vehicles), aerospace, marine, medical, industrial, telecommunications, and large-scale grid energy storage systems. Because of the nature of the context – previously unstudied, highly dynamic, and decidedly consequential for the world economy – I was unable to pre-specify empirical hypotheses or theoretical claims that would have warranted the use of hypothetico-deductive methods. Therefore, in this chapter, I follow an Inference to the Best Explanation (IBE) approach to arrive at the "best" explanation to an observed empirical puzzle (Goldfarb et al., 2022).

From the contextual deep dive into the evolution of the Li-ion battery industry, I observed two anomalies: (1) *multiple waves of new firm entry* and (2) *more than one instance of sales takeoff* (i.e., "hockey-stick" growth). Whereas prior research on industry evolution would have predicted declining rates of new firm entry (i.e., shakeout) amid industry sales growth and a single instance of sales takeoff (Gort & Klepper, 1982; Moeen et al., 2020). Based on industry studies in strategy research, I use three different theories of industrial change – *Industry Emergence (IE), Market Transformation (MT), and Disruption* – as possible explanations to infer which one best explains the observed anomalies in the evolution of this industry. To prefigure my preferred explanation, I propose a conceptual framework of Market Transformation that is qualitatively related to, but distinct from, the traditional frameworks of both IE and Disruption (Foster, 1986; Christensen, 1997). I define *Market Transformation* as a temporal process by which actors and firms engage in efforts of reconfiguring industry knowledge and beliefs because of an unexpected rise of uncertainty triggered by an application-related market demand shock (Goldfarb & Kirsch, 2020; Pontikes & Rindova, 2020; Ozcan & Hannah, 2020).

To establish why we need to import a new explanatory framework to this context, I first describe the general process by which the Li-Ion battery industry arose. Following this initial exegesis, I will compare the predictions of the IE and Disruption approaches with what I observed. These observations inform my assessment of the explanatory power of existing IE and Disruption approaches to industry emergence. At a minimum, these observations suggest possible boundary conditions of the IE and Disruption frameworks. Alternatively, I propose that the MT framework provides a better explanation for the observed evolutionary trajectory of the Li-ion battery industry.

This study contributes to strategy research on emergence and market evolution in several ways. First, it introduces an important, new industry to our existing repertoire of known industry case studies. Although my findings are context-specific, the Li-ion battery industry – unlike many of the other settings in which researchers have identified seeming regularities in industry evolution – is one that is now rapidly coming to be seen as a bellwether of the global economy, with tens of billions of dollars being invested across multiple companies and countries around the globe. It is "general-purpose" (like the laser), but it is also large and pervasive, and in this sense knowing that a theory of industry emergence explains activity in this industry may have greater relevance because of its demonstrable economic importance. Our scholarly assessment of the value of a theory of industry emergence should reflect, in some way, the importance of that industry to our general understanding of economic activity. A "parsimonious," "precise," and "consilient" explanation of a trivial industry faces a greater hurdle to generalizability. Knowing how the Li-ion battery industry evolved is, potentially, more meaningful – more "lovely" – than knowing how a less-important industry evolved.

Second, the MT explanation helps us understand how it was possible that in this context, *uncertainty was dynamic* (Goldfarb & Kirsch, 2020; Ozcan & Hannah, 2020). It did not decrease linearly over time as would have been predicted under a traditional IE regime; rather, uncertainty decreased and then increased, as actors (e.g., technology pioneers, serial entrepreneurs) and firms used the Li-ion battery technology in the electric vehicle market. Furthermore, although the Disruption framework would have explained an increase in uncertainty, that approach would also have necessitated a discontinuity in the prevailing technological regime (i.e., transition from Li-ion to some novel chemistry or other technological system). However, throughout the evolution of the Li-ion battery industry, I observe no such instance of discontinuous technological change. Although the industry has gone through many cycles of innovation, the basic battery chemistry of 2023 is unchanged from that commercialized in 1991. I do not observe a technological shock that would support a Disruption-based explanation.

Third, the MT framework is consistent with additional, observed empirical regularities, including (a) the Li-ion battery industry experienced *more than one instance of sales takeoff*, first for consumer electronics and subsequently for electric vehicles; and (b) I document multiple waves of *new firm entry* amid sales growth, a phenomenon that is inconsistent with the industry emergence theory. According to the IE approach, we would have expected to observe only sales growth and not a subsequent wave of new firm entry. I note that the Disruption approach would be consistent with these observations, but as noted above, I do not observe the technological discontinuity that is required in the Disruption model, such as a shift to a new, discontinuous S-curve.

Fourth, by documenting the processes by which actors and firms reconfigured industry knowledge and beliefs when faced with increasing uncertainty, this study offers new methodological insights for future studies of industry emergence, market transformation and disruption. The proposed MT framework underscores the need for *context-specific periodization* informed by understanding of the nature of uncertainty and entry for the generation of a meaningful account of a new, dynamic, and economically consequential industry. In this respect, the MT approach emphasizes the *before* and *after* as temporally distinct phases of the ongoing process of market emergence, while temporal periodization is more of an afterthought or a deterministic consequence of the IE and Disruption approaches.

To proceed, in section 2, I provide a brief description of the emergence and evolution of the Li-ion battery industry. Then, in section 3, I document the evolutionary trajectories of the Li-ion battery industry, in terms of new firm entry and sales, that enabled me to compare how each approach – IE, MT, and Disruption – would explain the dimensions associated with the industry evolution in this context. In section 4, by periodizing the evolution of the industry into three distinct periods, I contextually reason how the dimensions of uncertainty associated with each potential application market (and its relative size) changed over time. To infer the best explanation, I map the evolution of the Li-ion battery industry to the three frameworks – IE, MT, and Disruption – to elaborate on and evaluate how each framework would explain the empirical puzzle observed in the evolutionary trajectories. Then, in section 5, I discuss the implications of the study for theories of industry evolution in Strategic Management and provide three conjectures to be explored in future research. Finally, in section 6, I summarize the key findings, discuss possible limitations, and conclude.

2. CONTEXT: EMERGENCE & EVOLUTION OF THE LI-ION BATTERY INDUSTRY

Comparing the predictions of the IE and Disruption approaches with those of the proposed MT framework required an expansive and precise contextual knowledge of the evolution of the Li-ion battery industry. Thus, in this section, I document the historical account of the emergence and evolution of the Li-ion battery industry, which includes triggers of critical events, entrepreneurial actions by actors and firms, and industry milestones.

2.1 Incubation: Energy crisis, scientists, & scientific discoveries

The efforts in generating the industry knowledge base can be traced to different triggers. It could be argued that it was the oil crisis in the 1970s that motivated experimentation efforts by researchers and strategic investments by energy corporations towards oil alternatives and new energy sources (Sine and Lee, 2009). Regardless of the initial triggers during the incubation period, in retrospect, the discoveries of three scientists (Stanley Whittingham, John Goodenough, and Akira Yoshino) played a key role in generating the scientific knowledge base for the commercialization of the Li-ion battery technology. In 2019, the three scientists earned the Nobel Prize in Chemistry for their significant contributions to the development of the Li-ion battery (The Royal Swedish Academy of Sciences, 2019).

In the 1970s, chemist Stanley Whittingham discovered the concept of intercalation electrodes and, with a group of scientists at Exxon, demonstrated the first instance of a rechargeable Li-ion battery by combining a lithium metal (Li-metal) anode and a titanium sulfide (TiS) cathode (Whittingham, 1976). Given the chemical properties of the battery's components, the applicability of Whittingham's Li-ion battery was limited to coin cell-level batteries that were suitable for watches (Mizushima et al., 1980). In 1980, as the oil crisis was ending, energy companies, like Exxon, suspended their battery research. Still, Whittingham's workable battery prototype and other battery research had sparked wider research interest in developing next-generation battery technology.

By 1980, at the University of Oxford, physicist John Goodenough and his colleagues expanded on Whittingham's work and discovered a new type of cathode –

i.e., lithium-cobalt-oxide, LCO (Mizushima et al., 1980). Thus, they found that replacing the previous titanium sulfide cathode with a LCO cathode (commonly used today in Li-ion batteries for consumer electronic products) would result in a battery technology that was safe, stored more energy, and provided more freedom for the choice of anode material (Li et al., 2018).

Thereafter in 1985, chemist Akira Yoshino, while working at the chemical company Asahi Kasei, discovered that replacing the Li-metal anode with petroleum coke (a type of carbon material) significantly reduced fire risks from the battery. Thus, Yoshino paired his anode with Goodenough's LCO cathode and the other main battery components (i.e., separator, electrolyte, and other additives) and patented the Li-ion battery technology (Yoshino et al., 1987), which laid out the fundamental principles of the first commercialized Li-ion battery technology.

It is important to note that ever since the first rechargeable battery was invented in 1799 ("voltaic pile" by Alessandro Volta), every battery technology is comprised of four key components: "two electrodes – an [1] *anode* and a [2] *cathode* – dipped in a conductive solution (called an [3] *electrolyte*) with a [4] *separator* that controls the flow of the electric charge" (Rathi, 2019). In a Li-ion battery, those key components interact together through a nano-scale chemical process called intercalation. Compared to incumbent battery technologies (e.g., lead acid, NiCd, NiMH), and among its other distinguishing attributes, a Li-ion battery has higher energy density, which means it can store more energy in a smaller space. However, the Li-ion battery is more costly and has the risk of thermal runaway that can cause catastrophic fires to the end-product. In addition, each type of Li-ion battery chemistry differs in key performance indicators (i.e., energy density, power, safety, performance under different temperatures, life span, and cost). So, battery innovators must make trade-offs (e.g., higher energy density, higher risk on safety concerns) and go through thousands of material iterations to achieve the desired performance indicators without harming the already demanded attributes in a particular application (e.g., higher energy density and lower cost for electric vehicles).

By documenting the critical events during the incubation period (Moeen & Agarwal, 2017), I was able to identify the scientific discoveries by actors and firms that eventually culminated with the commercialization of the Li-ion battery industry. While initial efforts were intended to develop Li-ion battery technology as an alternative energy source to oil, the technology ended up being commercialized in a consumer product: a camcorder. This underscores the considerable technological and application market uncertainty associated with a technology – i.e., Li-ion battery – to be identified as a general-purpose technology (GPT) during the incubation period (Goldfarb, Taska, & Teodoridis, 2023). In other words, the efforts during the incubation period did not culminate with the commercialization of a GPT, but rather they led to its commercialization in a specific application market.

2.2 Commercialization & sales takeoff in the consumer electronics market

The Li-ion battery was first commercialized in 1991 by Sony Corporation, a global electronics conglomerate. It enabled them to introduce a smaller and lighter consumer electronic product: the TR1 8mm camcorder (Nishi, 2001; Blomgren, 2016). Shortly after Sony's successful commercialization, Asahi Kasei and Toshiba formed a partnership (A&T Battery Co.) that resulted in commercializing the Toshiba Portege

T3400CT, first laptop with Li-ion battery technology in 1993. By 1994, Motorola commercialized the MicroTac Elite, the first cellphone with Li-ion battery technology. The commercialization of the Li-ion battery demonstrated an instant success in the consumer electronics market when Sony sold three million units and then 15 million units of Li-ion batteries in 1993 and 1994, respectively (Rathi, 2019). In 1995, sales for Li-ion batteries took off alongside the increasing demand for laptop computers and cellphones.

As the sales of Li-ion batteries increased with the demand for consumer electronics (e.g., laptops and cell phones), it incentivized further experimentation efforts that aimed at advancing the technical performance of the Li-ion battery technology. Notably, in 1996, Professor John Goodenough, Akshaya Padhi, and their coworkers discovered a new type of cathode for Li-ion batteries. These lithium-iron phosphate (LFP) cathodes are currently being used for Tesla's Model 3 and they are supplied by Contemporary Amperex Technology Limited (CATL), one of the largest battery manufacturers.

By mid-2000s, on a global market-level, not only did Li-ion batteries account for 75% of the rechargeable battery business, but there were also advanced versions of Li-ion battery technology that delivered more energy for power tools. In addition, the Li-ion battery gained a broader interest across other application markets, such as vacuum cleaners, ride-on lawn mowers, and hybrid electric vehicles (Bulkeley, 2005). By the mid- to late-2000s, there was an influx of new firm entries, investments by venture capitalists and corporations, and governmental grants in the space of clean energy technologies.

By documenting the early stage of the Li-ion industry after it was first commercialized, I provide evidence that most of the initial efforts by actors and firms (i.e., incumbent battery manufacturers) were focused on developing the Li-ion battery technology for the consumer electronics market. By the early 2000s, while there were innovative efforts by battery start-ups (e.g., A123 Systems) in developing Li-ion battery technology for hybrid electric vehicles, most incumbent battery manufacturers (e.g., Sony, Sanyo) were more focused on scaling Li-ion batteries for the consumer electronics market.

2.3 New application market: Electric vehicles

In 2006, the introduction of the Tesla Roadster triggered a demand-side shock for the Li-ion battery industry. The scale standards of Li-ion batteries required in an electric vehicle and the size of such a market were difficult to predict due to several industry dynamics. For instance, while the US start-up automaker Tesla decided to produce electric vehicles with thousands of laptop Li-ion batteries, traditional automakers, like Toyota, were producing hybrid electric vehicles with a significantly smaller number of large-format purpose-built NiMH batteries (i.e., Nickel-metal hydride – incumbent battery technology). Thus, incumbent battery manufacturers, like Panasonic, that were supplying the batteries for both automakers, faced critical uncertainty in terms of the expected growth of such an application market, and the scaling capabilities that were required to meet the future demand across multiple application markets.

In June 2010, Tesla Motors shares rose nearly 41% on its first day going public, signaling an intriguing emerging electric vehicle market for actors and firms in the Li-ion battery industry. By 2012, Tesla delivered approximately 2,450 Roadsters to customers in over 30 countries (Tesla Motors, 2012). Tesla's success for its architectural Li-ion battery system in the Roadster attracted more interest from incumbent battery manufacturers (i.e., Sanyo, Panasonic) and traditional automakers (i.e., Daimler and Toyota), and that interest increased when Tesla successfully commercialized its second electric vehicle, the Model S. In 2013, the Model S was the first electric vehicle to win the "Motor Trend Car of the Year" award, by all measures used to determine the best car each year – i.e., advancement in design, efficiency, engineering excellence, performance of intended function, safety, and value (Yeadon & Mackenzie, 2012).

While we can clearly date the initial resurgence of uncertainty to the introduction of the Tesla Roadster, I am unable to provide the same type of evidence for the end of this period. I acknowledge that dating the start and end of this period using the introduction of two vehicles by one company is admittedly somewhat arbitrary. However, in section 4, I provide a deeper exploration of this phenomenon (i.e., dating the start and end of this period) and consider the consequences of emplotting other periodization.

2.4 New market growth, competing strategies, & sales takeoff in the electric vehicle market

Amid the then-emerging (mid to late 2000s) electric vehicle market and complexities involved in manufacturing Li-ion batteries for such a market, battery manufacturers chose different business models to scale with no consensus of what would be the "winner-take-all" strategy. While battery manufacturer Amperex Technology Limited (ATL) chose to spin off another company, Contemporary

Amperex Technology Co. Limited (CATL), to produce and supply Li-ion batteries solely for the electric vehicle market (i.e., *supply strategy*), Panasonic signed an agreement with Tesla to build a large-scale Li-ion battery manufacturing plant in the US – known as the GigaFactory – for Tesla's electric vehicles and stationary storage technology *(i.e., alliance strategy)*.

In 2016, the electric vehicle market (i.e., hybrid electric vehicles, plug-in electric vehicles, electric buses) accounted for almost 43% of Li-ion battery demand. By 2022, the electric vehicle market had grown to approximately 80% of the Li-ion battery demand (Wood Mackenzie, 2022)

The technological developments in advancing the Li-ion battery performance, improving its manufacturing processes, and significantly reducing its cost have led to its widespread adoption across different application markets (Ziegler & Trancik, 2021). However, the documented industry dynamics underscore the importance of closely examining the unfolding of context-specific events and the related entrepreneurial actions by actors and firms to better understand the process of market transformation in the Li-ion battery industry. Otherwise, the considerable entrepreneurial actions that led to the subsequent event of sales takeoff in the electric vehicle market would be understudied by following the approaches of both IE and Disruption. Importantly, from the perspective of actors and firms in the Li-ion battery industry, the new electric vehicle market was considerably different from the consumer electronics market in terms of size, scale of Li-ion batteries required per product, and complexities. Although both application markets may use the same type of Li-ion battery cell chemistry, the magnitude of engineering problems, breadth of technological complementarities, and challenges of scaling were fundamentally different.

3. OBSERVED EMPIRICAL PUZZLE IN THE EVOLUTION OF THE LI-ION BATTERY INDUSTRY

After reviewing the high-level trends in the emergence and evolution of the Li-ion battery industry, in this section I look more deeply into the industry dynamics that characterized this period (1991—2023). To systematically evaluate the predictions of IE, Disruption, and the proposed MT frameworks in explaining the evolution of the Li-ion battery industry, I document the evolutionary trajectory of this industry in terms of sales and new firm entry. I consider the industry dynamics between the period of industry emergence of the Li-ion battery industry for the consumer electronic market, during the 1990s and early 2000s, along with the time period when it became clear that there existed a market of Li-ion batteries for electric vehicles following the introduction of the Tesla Roadster in 2006.

3.1 Observation 1: Application market size & scale; consumer electronics vs. electric vehicles

Consistent with prior industry studies to observe the evolutionary sales trajectory of the industry, I document the demand for Li-ion batteries across two potential application markets – i.e., consumer electronics and electric vehicles (as illustrated in Figure 2-1) – that have driven the growth of the industry. I rely upon the Ziegler & Trancik (2021) dataset that assembled the total market size for the Li-ion battery (by sales in megawatt-hour, MWh) from 1991 to 2016 by using multiple resources, such as journal articles, conference papers, government reports, press releases, industry presentations, manufacturer catalogs, magazine articles, and book chapters. Furthermore, I collected data from industry reports published by Bloomberg New Energy Finance (BNEF) that have been tracking industry events and demand for Li-ion batteries across multiple application markets from early 2010s to present (2023), which includes both consumer electronics and electric vehicle markets.

[Figure 2-1 about here]

Brief observations follow from documenting the evolutionary sales trajectory regarding the size of each potential application market and the scale of Li-ion batteries required for each application. First, the Li-ion battery technology was not born "general-purpose" but rather was commercialized in different application markets over time, starting in the consumer electronics market and then in the electric vehicle market. In fact, the same basic battery technology that was initially commercialized in the consumer electronics domain (e.g., camcorders, laptops, cell phones), by the end of my study period, had also found widespread adoption in the electric vehicle sector (e.g., hybrid and plug-in electric vehicles). For more than a decade, the market size for Li-ion batteries in the consumer electronics market was significantly larger than that in the electric vehicle market. The sales trajectory for Li-ion batteries in the consumer electronics market has been growing ever since its first commercialization. However, the industry experienced a *subsequent wave of sales takeoff* from the increasing demand of Li-ion batteries in the electric vehicle market, which surpassed the demand for Li-ion batteries (in kWh) in the consumer electronics market. This phenomenon is inconsistent with the IE theory, in which we would have expected to observe a single instance of industry sales takeoff.

Second, although there were more units sold of consumer electronic products than electric vehicles, importantly, the scale of batteries required in each application was significantly different. While laptops would commonly have four to six Li-ion battery cells, an electric vehicle required thousands of those same Li-ion battery cells. In the case of the Tesla Roadster, it required 6,831 laptop Li-ion battery cells. Such a difference in the number of Li-ion batteries required per application market presented incumbent battery manufacturers with challenges to scale production of Li-ion batteries for the expected future demand in the electric vehicle market based on their production-scaling capabilities for the established consumer electronics market. In other words, manufacturing Li-ion batteries and integrating them into electric vehicles entailed different layers of technological systems complexity that was not initially apparent for actors and firms in the Li-ion battery industry. Rather, such layers of systems complexity were discovered over time through experimentation and development efforts (See below for contextual details in *section 4.2.2 Resurfacing Uncertainty: 2006—2012*).

3.2 Observation 2: New firm entry by US-based battery start-ups

To document the evolutionary trajectory of the Li-ion battery industry in terms of new firm entry and exits, I used multiple sources to gather quantitative data on US-based battery start-ups founded between 1991 and 2022.

The data-generating process in collecting the quantitative data of US-based Li-ion battery start-ups started with a general search of firms in the battery manufacturing industry identified in the S&P Capital IQ database according to the Standard Industrial Classification (SIC) codes 3691 (storage batteries – rechargeable) and 3692 (primary batteries – non-rechargeable). Although the SIC code 3692 indicated firms engaged in manufacturing non-rechargeable batteries, it was necessary to tease out the diversifying entrants from start-up entrants. Then, for the firms in SIC 3691, I went through each company's "Business Description" – as documented by the S&P Capital IQ – by keyword search (see Table A-1 in Appendix) to distinguish the firms innovating in Li-ion batteries from those engaged in only developing incumbent rechargeable battery technologies (i.e., lead acid, NiCd, and NiMH).

Then, I identified and matched Li-ion battery start-ups that were listed as attendees in the International Battery Seminar (industry conference, est. 1983) during the period 2019—2021, as members in the NAATBatt International (not-for-profit trade association, est. 2007), as members in the New York Battery & Energy (Consortium, est. 2010), and those that were listed as battery start-ups in other databases, such as, i3 Connect (known for tracking global data on Clean-Tech firms), Crunchbase, and Pitchbook.

In the dataset, start-ups were identified as new entrants if they had no existence prior to entering the industry, or they were spinouts that are entrepreneurial ventures of ex-employees of industry incumbents, which are considered as a subcategory of start-up entrants, and they were not an incumbent-backed firm (i.e., joint ventures, subsidiaries), which are considered as separate legal entities with formal ties (Kapoor & Furr, 2015). The final sample is the population of 151 new entrants that were founded in the US as innovators at the battery cell-level.

Figure 2-2 shows the patterns of US-based start-up entry and exit throughout the evolution of the Li-ion battery industry. The green bars represent the number of new firm entry, whereas the red bars represent start-up exits (via acquisition or out of business), and the gray bars represent the yearly cumulative number of start-up entrants. It is important to note that, during the observed period, the cumulative representation also includes start-ups that exited which totaled 42 exits, thereby limiting the survival bias in the analysis.

[Figure 2-2 about here]

While patterns of new firm entry can be observed across the multi-decade history of the Li-ion battery industry, there was still an increasing number of new firm entry by battery start-ups after the point of initial sales takeoff, which was critical on the competitive landscape. In other words, the Li-ion battery industry experienced a *wave of new firm entry* after the industry's initial sales takeoff. An observation that was inconsistent with the IE theory, as we would have expected to observe only sales growth after the point of sales takeoff and not subsequent waves of new firm entry. Furthermore, I do not observe an event of technological discontinuity (such as a shift to a new, discontinuous S-curve) as that is when we would have expected a wave of new firm entry in a Disruption-based model.

4. FRAMEWORKS FOR UNDERSTANDING NON-CONFORMING OBSERVATIONS

4.1 Framework 1: How do we locate uncertainty in evolving industry settings?

Theories of both IE and Disruption commonly associate waves of new firm entry to early stages of an emerging industry, market, or technology which is characterized by a period of high uncertainty. Thus, to document the uncertainty faced by actors and firms, I decompose and analyze multiple dimensions of uncertainty associated with the emergence and evolution of the Li-ion battery industry (Goldfarb & Kirsch, 2019; Moeen et al., 2020; Kapoor & Klueter, 2021).

Since the commercial value of a Li-ion battery technology is realized when embedded in an actual product, in an application market, I suggest that a critical trigger of different levels and dimensions of uncertainty associated with the evolution of this industry was rooted in the discovery and commercialization processes of a potential application.

Thus, *application market uncertainty* refers to the lack of knowledge and beliefs about the expected future size, scale of batteries required per product, and breadth of possible application markets for Li-ion battery technology. Such uncertainty is exacerbated especially when actors, firms, and customers themselves are unaware of their latent and explicit preferences (Christensen & Bower, 1996; Adner & Levinthal, 2001; Shermon & Moeen, 2022). For instance, neither the applicability nor commercial value of the Li-ion battery technology were well-recognized in the application market of electric vehicles ex ante, based on its technical features and commercial viability in the initial consumer electronics market.

The introduction of application market uncertainty potentially triggered *technological uncertainty* which refers to the lack of knowledge about the Li-ion battery technology's "technical designs comprising of technical components and their connecting architecture" (Moeen et al., 2020, p.221), as well as the breadth of complementarities and their recombination within different technological systems that only develops over time (Arthur, 2007, 2009; Goldfarb & Kirsch, 2020). In other words, the nature and speed of technological development is often a complex process

(Goldfarb & Kirsch, 2019), which makes it difficult for actors and firms "to predict how the technology would improve over time as a function of the effort expended and whether those improvements would be adequate to generate performance superiority over the prevailing technologies" (Kapoor & Klueter, 2021, p.65). For instance, given the fact that a Li-ion battery is an electrochemical device, its technical failures can be catastrophic (e.g., overheating a Li-ion battery can cause fire). Ways of resolving such technical issues were not initially obvious to industry actors and firms but rather were discovered through further efforts of development and experimentation over time. Although similar Li-ion battery cell technology was used in consumer electronics and electric vehicles, it is important to consider that the architectural battery systems for each application market were different in terms of systems complexity. In addition, each application market presented actors and firms with different challenges to scale production of Li-ion batteries.

Furthermore, when the Li-ion battery technology was commercialized in the Tesla Roadster, its technical and commercial viability were not well-established. Thus, it triggered *competitive uncertainty,* which refers to the lack of knowledge about the possibility of new firm entry and their capabilities (Goldfarb & Kirsch, 2019), which can potentially play a critical role in reconfiguring industry knowledge and beliefs. For instance, while the industry experienced a low number of new entrants after the Li-ion battery technology was first commercialized in consumer electronics, the industry experienced an increasing number of new entrants when there was increasing uncertainty around the application of Li-ion batteries in electric vehicles.

There was also considerable *business model and value chain uncertainty* which refers to the lack of knowledge of how firms will create and capture economic value for their Li-ion battery technologies across different application markets. For instance, when a battery pack containing 6,831 Li-ion battery cells became a viable architectural design for electric vehicles, it was not obvious for incumbent battery manufacturers what business models and value chain activities were required to be better positioned for appropriating value from such a new application market. In other words, the then-emerging electric vehicle market generated a “no winner-take-all” environment in the Li-ion battery industry. The incumbent industry standards in terms of manufacturing processes and capabilities for mass-production of Li-ion batteries, which were initially focused for the consumer electronic market, were not sufficient to meet the expected future demand of Li-ion batteries in the electric vehicle market.

Lastly, in such industry dynamics, there was also considerable *institutional uncertainty* (i.e., social legitimacy and regulation) with respect to the role and efforts of other industry actors, such as government agencies and investors. For instance, when the US government issued tax incentives for new qualified electric vehicles and grants for battery development, it was difficult to predict how such institutional stimulators would influence the automakers’ standards and requirements for battery technology that would be considered in their production processes for electric vehicles, and whether such subsidies would increase the adoption of electric vehicles by customers. From the perspective of investors, such as venture capitalists, it was not obvious how their standard business models of financing ventures would fit with the development of battery technologies that was a multi-stage, multi-year process.

Overall, in the case of the Li-ion battery, when it was first commercialized in the consumer electronics market and then later in the electric vehicle market, application market uncertainty played a critical role because each application market triggered different levels and dimensions of uncertainty across different periods. Only when actors and firms had reconfigured sufficient industry knowledge and beliefs across multiple dimensions of uncertainty that enabled scalability and cost-effectiveness, did the Li-ion battery industry experience a second wave of sales take-off, which represented viable commercial activity in a subsequent application market. Thus, by distinguishing the dimensions of uncertainty that are salient at different times and examining how they were addressed and resolved, we can better understand the market transformation process.

4.2 Framework 2: Why do we use the historical lens to periodize change?

For a systematic investigation of the temporal process of market transformation, "the use of the historical lens is necessary not only because it affords a retrospective view, but also because it requires the researcher to place themselves in the context of their subject" (Goldfarb & Kirsch, 2020, p.8). In addition, a historical lens allows the researcher to construct narrow findings to adjudicate and differentiate between possible explanations for the observed puzzle, which is an integral iterative process in the IBE approach (Pillai, Goldfarb, & Kirsch, 2021). Thus, to document critical industry events, I gathered qualitative data by using multiple sources: business history of companies (e.g., incumbent battery manufacturers, battery start-ups, automakers), conference papers and presentations (e.g., International Battery Seminar, Advanced Automotive Battery Conference), article databases (e.g., Factiva, Nexis Uni), industry reports (e.g., Bloomberg New Energy Finance Reports, Annual Battery by Volta Foundation), books (e.g., Schallenberg, 1982; Higgins, 2021; Eisler, 2022), and an online battery community (e.g., Battery Brunch).

By using a historical lens, I was able to construct narrow findings of critical industry events, identify the distinct periods that were characterized by different levels of uncertainty, and highlight the distinguishing features of the market transformation process in the evolution of the Li-ion battery industry. Therefore, in this section, I briefly elaborate on the three distinct periods I have identified in the evolution of the Li-ion battery industry. Then, I provide contextual reasoning to the dimensions of uncertainty associated with each potential application market that actors and firms faced. I argue that the efforts of (re-)configuring industry knowledge and beliefs by actors and firms fundamentally shaped the observed evolutionary trajectories of the Li-ion battery industry.

First, during the *Preliminary Market Era (1991—2005)*, the industry efforts of configuring industry knowledge and beliefs across the dimensions of uncertainty were focused primarily on the consumer electronics market, since there was no clear commercial value nor technical viability for Li-ion battery technology in the electric vehicle market. According to industry experts, the Li-ion battery technology required further development, and its high cost would have increased the total price of an electric vehicle, which was not a desirable attribute for mass adoption. The period ended with the commercialization of the Tesla Roadster, which resembled a proof-of-concept for using laptop Li-ion batteries in an electric vehicle.

The first period demonstrated a time in which considerable industry knowledge and beliefs were developed for the consumer electronics market, while not considering the potential applicability of Li-ion batteries for the electric vehicle market. While the traditional automakers were producing electric vehicles by experimenting with incumbent battery technologies (i.e., lead acid, NiMH), the incumbent battery manufacturers were focusing their efforts on mass-producing Li-ion batteries to meet demand in the initial consumer electronics market. Consistent with explanations provided by the IE framework (Moeen et al., 2020), the initial sales takeoff of Li-ion batteries in the consumer electronics market would imply reduction of uncertainty as industry actors and firms had generated considerable industry knowledge and beliefs across multiple dimensions of uncertainty for that market.

Second, during the period of *Resurfacing Uncertainty (2006—2012)*, actors and firms in the Li-ion battery industry experienced increasing uncertainty triggered by the dynamics in two potential application markets, i.e., less by the consumer electronics market and more so by the then-nascent electric vehicle market.

In the second period, the commercialization of the Tesla Roadster (i.e., triggered by the development of the t-zero) represented a proof-of-concept of an electric vehicle using laptop Li-ion battery technology. Initial attempts to combine thousands of laptop Li-ion battery cells as the battery system for an electric vehicle seemed promising. However, there was unsettled technological uncertainty, such as the scale of batteries required for electric vehicles and battery fires that could be catastrophic. Such application-related market demand shock forced industry participants into a high-uncertainty environment that required the reconfiguration of industry knowledge and beliefs. For instance, given the fact that an electric vehicle required thousands more battery cells than consumer electronics did, entering this new market required considerable efforts in reconfiguring industry knowledge and beliefs to address the scaling issues to accommodate the future expected demand of Li-ion batteries across multiple application markets and the battery safety concerns (i.e., monitoring each battery cell electronically).

Finally, the *Reconfigured Market (2013—2023)* period depicts the efforts of reconfiguring industry knowledge and beliefs to address the challenges of scaling that considered different application markets, which culminated in a subsequent wave of sales takeoff in the electric vehicle market. In other words, only when sufficient industry knowledge and beliefs were reconfigured across multiple dimensions of uncertainty for the transformed Li-ion battery industry did it reach the subsequent sales takeoff milestone.

4.2.1 Preliminary Market Era: 1991—2005

When Sony Corporation successfully commercialized the Li-ion battery for its camcorders in 1991, the path to commercialize Li-ion batteries in consumer electric vehicles was far from obvious, especially when there was no real electric vehicle market for Li-ion batteries.

Shortly after Sony commercialized the Li-ion battery for its camcorders, Li-ion batteries were commercialized in other consumer electronics, such as laptops and cell phones. The notion of a rechargeable battery technology that had higher energy density, lighter weight, smaller size, and longer life differentiated the technical features of the Li-ion battery from those of the other competing battery technologies, such as nickel-cadmium (NiCd) and nickel-metal hydride (NiMH), in the consumer electronics market. Initial industry efforts by incumbent battery manufacturers to scale production of Li-ion batteries were primarily focused on the growing demand in the consumer electronics market. No incumbent battery manufacturer who was focused on the consumer electronics market considered mass-production of Li-ion batteries for the electric vehicle market. By 1995, industry sales of Li-ion batteries took off alongside the demand in the consumer electronics market, as application producers recognized that shifting to Li-ion batteries would enable them to commercialize lighter, thinner, and longer-lasting technological products. Thus, the commercialization of the Li-ion battery across multiple consumer electronic products within a short period would imply that industry participants (i.e., incumbent battery manufacturers, product producers) had reduced considerable uncertainty at the nexus of technology and application market for consumer electronics.

In addition, competitive uncertainty was considered low because the overall Li-ion battery production business was primarily dominated by global electronics conglomerates such as Sony and Sanyo. Those incumbent battery manufacturers were engaged in either solely producing batteries or producing both batteries and downstream consumer electronic products. Such an oversupplied battery industry made it extremely difficult for battery start-ups to enter and compete as battery manufacturers. Similarly, uncertainty with respect to business model and value chain was considered low. The growing market demand in the consumer electronics market was sufficiently met by the mass-production capabilities of incumbent battery manufacturers. Thus, in such a highly integrated value chain that was optimized towards the consumer electronics market, a likely path for battery start-ups, in terms of a business model, was to partner with incumbent battery manufacturers or license their battery technology. For instance, battery start-ups, like T/J Technologies, were founded based on a cell-level innovation (i.e., cathode or cell design), aiming to create value for batteries in the consumer electronics market and capture value by trading in intermediate markets (i.e., "markets for technology"). In contrast, a more ambitious path for start-ups, such as the one pursued by PolyStor Corporation or A123 Systems, was choosing to become a battery manufacturer and compete against incumbent battery manufacturers.

Since Li-ion was considered as a competing battery technology, it did not require significantly different regulations (i.e., importation/exportation activities) than those that were already in place for existing battery technologies for the consumer electronics market. Thus, uncertainty regarding the institutional dimension was relatively low not only from a regulatory perspective but also because the adoption of Li-ion battery technology across multiple consumer electronic applications within a short period suggested higher social legitimacy.

On the other hand, the overall uncertainty associated with the application market for electric vehicles was somewhat latent because such demand did not exist for the Li-ion battery industry. While the initial industry sales took off in the consumer electronics market, there was no commercial activity for the Li-ion battery in the electric vehicle market. The auto industry itself was undergoing a period of technological competition among traditional automakers that selected alternative battery technology for their electric vehicles.

Although not stemming from the application market uncertainty for battery technology for use in electric vehicles, there was considerable institutional uncertainty in terms of governmental efforts to encourage traditional automakers to introduce electric vehicles to counter the environmental crisis. For instance, the US government pointed to efforts by industry participants in the auto and energy sectors towards the need of developing and funding electrochemical energy storage technologies that would support the commercialization of electric vehicles. Notably in 1990, the California Air Resources Board (CARB) pioneered the Zero-Emission Vehicle (ZEV) mandate, which required traditional automakers' new vehicles sold in California market to include 2% ZEVs in 1998, 5% ZEVs in 2001, and 10% ZEVs in 2003. To find viable solutions that met the requirements of the ZEV mandate, in 1991, the US Advanced Battery Consortium was formed as a cooperative initiative that bridged participants between industry and the US government. The major industry participants included Chrysler, Ford, General Motors (GM), Electric Power Research Institute (EPRI), and the Department of Energy (DOE). By 1997, in efforts to meet the regulatory requirement of the ZEV mandate, traditional automakers commercialized electric vehicles, which also marked the first attempt of using the Li-ion battery technology in an electric vehicle only by Nissan. Yet, in the early 2000s, traditional automakers (i.e., GM, Ford, Honda, Toyota, Nissan) halted their production of electric vehicles and discarded their leased and commercialized fleets off the market (see Paine, 2006 for documentary). This triggered further uncertainty at the technology-application market nexus for the Li-ion battery industry for electric vehicles. Thus, it demonstrates the complex nature of technological uncertainty stemming from the application market that is salient not only during the incubation stage of the industry, but also during the post-commercialization stages.

Overall, application market uncertainty for electric vehicles was latent because the Li-ion battery was far from being considered as a viable choice of battery technology by the traditional automakers, primarily due to its high cost and required further developments. Using Li-ion battery technology in an electric vehicle was notionally possible and was thought of by industry experts as something that would happen in the distant future because it required further development (Mader, 1996). In other words, the short-term uncertainty of using Li-ion battery for electric vehicles was arguably low.

Traditional automakers were experimenting and exploiting incumbent battery technologies, such as lead acid and NiMH. For example, the re-emerging instance of the modern electric vehicle in 1997 included the commercialization of the GM EV-1 (initially used lead acid and then NiMH), Ford Ranger EV (initially used lead acid and then NiMH), Toyota RAV 4 (used NiMH), Honda EV Plus (used NiMH), Chrysler EPIC (used NiMH), and Nissan Altra (used Li-ion supplied by Sony). Important to note that the Nissan Altra was mainly used for testing in California as a fleet vehicle by electric utility companies. The high-cost Li-ion battery technology would have forced traditional automakers to offer an expensive electric vehicle, which was not an appealing value proposition for a mass-market adoption when compared with vehicles that had incumbent battery technologies or even more so with gasoline-powered vehicles. For example, while the GM EV1 that used lead acid batteries was priced at $33,959, the Nissan Altra that used Li-ion batteries was priced at $50,999 (Chan, 2002). Therefore, the latent nature of such an application market uncertainty would suggest that knowledge gaps across multiple dimensions of uncertainty for using Li-ion batteries in electric vehicles were left unresolved.

4.2.2 Resurfacing Uncertainty: 2006—2012

The introduction of the Tesla Roadster in 2006 triggered both excitement but also an increasing level of uncertainty at the technological-application market nexus with respect to using laptop Li-ion battery technology in electric vehicles. According to BloombergNEF's first industry coverage report on lithium-ion batteries:

> Most battery experts agree that the road taken by Tesla Motors, a US company that is developing a sports car powered by 6,831 lithium batteries of the kind normally used in laptops, is not where the future lies either. 'It's a Heath Robinson solution as far as battery technology is concerned,' says Aachen battery expert Professor Sauer. 'Each individual cell needs to be monitored electronically.' Holger Schuh of Nuremberg manufacturer Saft Batterien says the Tesla system is 'not a practicable solution,' not least because car and laptop batteries are designed for different purposes (Janzing, 2007, p. 17).

The commercialization of an electric vehicle with thousands of laptop Li-ion batteries marked a significant application-related market shock for the Li-ion battery industry. Based on historical records the introduction of the Tesla Roadster was an inflection point that triggered a shift of focus by industry actors and firms towards addressing industry knowledge gaps associated with the commercial opportunity of using Li-ion battery technology for electric vehicles. Yet, at the same time, the electric vehicle market was still viewed as risky by the incumbent battery manufacturers (Kelty, 2020).

The considerable technological uncertainty was not only triggered by the electric vehicle market but also partially from the established consumer electronics market. In 2006, the US consumer electronics market experienced the largest safety recall due to Li-ion battery fire incidents that were traced to either manufacturing defects or inefficiencies in the battery management systems (i.e., Thermal management). For example, Dell recalled four million laptops that contained Li-ion batteries supplied by Sony. Similarly, Apple recalled 150,000 laptops that contained Li-ion batteries supplied by LG Chem. The incidents raised critical uncertainty that resided at the technological-application market nexus that was expected to have been resolved preceding the industry's initial sales takeoff. In fact, the Li-ion battery fire incidents in the consumer electronics market were so severe that impacted the market leadership and profits of incumbent battery manufacturers. For instance, in 2006, battery recalls slashed Sony's profits by 40%, which totaled to a cost of $430 million (Pillot, 2010).

The unresolved technological uncertainty at the technological-application market nexus triggered considerable competitive uncertainty. Since incumbent battery manufacturers did not originally optimize their Li-ion battery technology and production systems for the electric vehicle market, such industry dynamics could have incentivized new entrants such as A123 Systems, Advanced Battery Technologies, and Farasis Energy to commercialize their Li-ion battery technology that targeted the initial consumer electronics market or the then-emerging electric vehicles market or both. In fact, between the mid- and late-2000s, there was an influx of new entrants, venture capital and corporate investments, and government grants in the space of clean energy technologies (e.g., advanced rechargeable battery technology). This dramatic increase in the number of new entrants suggests that the incumbent battery manufacturers did not have the winner-take-all strategy advantage in producing and supplying Li-ion batteries across multiple application markets as they had for the consumer electronics market.

In addition, there was also uncertainty with respect to the business model and value chain. For instance, although the incumbent battery manufacturers had significant mass-production capabilities, it was not obvious how they would reconfigure those capabilities to avoid catastrophic fire incidents. As the industry incumbents were addressing the uncertainty at the technological-application market nexus, it was not obvious to what extent the business models of new entrants would complement or disrupt the existing value chain for Li-ion battery production.

There was also institutional uncertainty in terms of what standards and regulations would be enforced to avoid such future catastrophic battery fires. While industry regulations and standards are institutional safeguards against future battery incidents, the cost implications of those safeguard mechanisms on battery incumbents or entrants were unclear.

The Tesla Roadster was a proof-of-concept for an electric vehicle that consisted of using 6,831 laptop Li-ion batteries attached together in modules and packs to form the vehicle's architectural battery system. Overall, it had better technical performance metrics, such as lighter weight and more range than the electric vehicles introduced during the Preliminary Market Era. More importantly, the proof-of-concept generated a new application market demand for the Li-ion battery industry. Yet, there was still considerable uncertainty at the technological-application market nexus for electric vehicles. For instance, battery safety concerns residing in the consumer electronics market further discouraged incumbent battery manufacturers, like LG Chem and Panasonic, from selling to or being associated with any electric vehicle start-ups or even traditional automakers using their batteries in electric vehicles (Higgins, 2021). As described by Kurt Kelty (in a podcast interview) who played a critical role on both sides, first in the Li-ion battery industry with Panasonic then in the electric vehicle market with Tesla:

> When I went from Panasonic to Tesla in 2006, I was in charge of finding a battery cell supplier, and you would think, 'Oh, that's easy, you would say you're Tesla and all the doors would open.' You have to recall, put yourself back in 2006, where Tesla was a nobody, and the battery industry looked down upon the EV industry in terms of a usage for Lithium-ion cells. The battery industry did not want to sell Lithium-ion cells to the EV companies because of the concern about safety. Lithium-ion cells, if handled poorly, are a safety concern, and they looked at any start-up or even any of the big OEMs [traditional automakers] just a real risky play. [...] So, none of the battery cell manufacturers wanted to deal with us. They didn't want anything to do with us (2020).

From a battery manufacturer perspective, the electric vehicle resembled an application market that did not depend on two to six battery cells per product, such as in camcorders, laptops, or cell phones, but depended on thousands of those similar battery cells per vehicle. Such a potential market would have been expected to generate more excitement from the Li-ion battery industry. Yet at the time, no battery manufacturer wanted to be involved in producing Li-ion batteries for the electric vehicle market. Such industry dynamics underscore the crucial uncertainty at the technological-application market nexus faced by industry actors and firms. In fact, it required many visits to Japan, by Martin Eberhard (Tesla co-founder), to convince Sanyo (one of the largest Li-ion battery manufacturers) to supply Tesla with Li-ion batteries: “In his pitch to a Sanyo factory manager, Eberhard reasoned that just one of the vehicles [Tesla Roadster] he was proposing required as many cells as 2,000 notebook computers, meaning that 1,000 such cars would require as many cells as two million notebooks” (Eisler, 2023, p. 71).

Furthermore, there was considerable competitive uncertainty triggered by the application market uncertainty for electric vehicles. For instance, after struggling to overcome many of its technical challenges regarding its proprietary electric powertrain system – i.e., batteries and motor – Tesla started delivering its first electric vehicles (Tesla Roadster) to its customers in 2008. Only in 2009 did incumbent battery manufacturers such as Panasonic eventually agree to supply Li-ion batteries to the electric vehicle market by partnering with Tesla Motors. Around the same time, the competition among US Li-ion battery start-ups intensified as they entered as battery-component innovators or battery cell-architecture disruptors. It was not clear whether or how any of the battery start-ups were going to develop the scaling capabilities to compete against the incumbent battery manufacturers.

The entry of new battery component innovators or battery cell manufacturers would imply that there was critical business model and value chain uncertainty. For instance, during the Preliminary Market Era, the most likely path to commercialization for any battery start-up innovator was to establish partnership deals in intermediate markets (i.e., market for technology) with incumbent battery manufacturers and/or product producers in the application market. For battery start-ups, securing supplier-partnership agreements signaled the potential applicability of their battery innovation (i.e., infusing cutting-edge industry knowledge). But when the industry was experiencing entry by battery start-ups following a more ambitious path to commercialization (i.e., manufacture battery cells and compete against incumbents), it triggered business model and value chain uncertainty within the Li-ion battery industry.

In 2009, Li-ion battery start-up A123 Systems had one of the biggest IPOs where its shares soared 50% on opening day. Such an IPO generated excitement for the Li-ion battery industry (Higgins, 2021), since by that time A123 Systems had secured multiple partnership deals with domestic and international automakers. Yet, it was not clear if it was a successful outcome for the start-up or simply a strategic fundraising technique to gain more leeway as they navigated the challenges of scaling production of Li-ion batteries for the electric vehicle market. In fact, A123 Systems not only secured a partnership with Black and Decker to supply batteries for their power tools but had also established partnership agreements with traditional and start-up automakers of electric vehicles (i.e., GM, Th!nk, Shanghai Automotive, Chrysler, Fisker Automotive) to supply batteries for electric vehicles.

Furthermore, by the early 2010s, CATL, a major Chinese battery manufacturer for the consumer electronics market, had to transform its mass-production capabilities for Li-ion batteries to consider the demand in emerging electric vehicle market (note: ATL – today known as CATL and one of the largest Li-ion battery manufacturers – was founded in 1999 to produce Li-ion batteries for the consumer electronics market and did not produce Li-ion batteries for the electric vehicle market until the early 2010s). As described by Herbert Diess (CEO of Volkswagen) during an interview:

> It's growth [demand for batteries], it's so much that no sole company would have been able to do all the investments […]. We are looking for external companies, the first plants [Giga-factories] finance ourselves but we will invest in batteries because so much growth is necessary, and we couldn't find enough suppliers to do the job […]. In 2012 or 2013, when I first visited a small company in China, which was called CATL. They would have a turnover of 200 million or so or 300 million. They'd do pouch cells for smartphones, for a big American customer. I visited them and said, I need battery cells for cars. First for plug-in hybrids and then for electric cars. And the guys looked at me and said 'Uff we can't do cars, it's too big! We don't have enough facilities.' And they were really not prepared. But I could convince them and CATL is now, and Robin Zeng [CEO and founder], and he made an exceptional transition, and now it's the second biggest battery manufacturer, market capitalization is about $200 billion, something like that, really fast growth, and it's extremely innovative (2022).

Before the Panasonic-Tesla partnership, it could be argued that there was business model and value chain uncertainty, in the sense that if incumbent battery manufacturers, with all their years of experience and scaling capabilities, were able to supply Li-ion batteries for the initial consumer electronics market and the then-emerging electric vehicle market simply by scaling production of Li-ion batteries, they would have done so. Yet, given the breadth of technological complementarities that were required to be developed and the immense scale of batteries required to meet the demand in the electric vehicle market, the Li-ion battery industry had to reconfigure its business model and value chain activities to accommodate the heterogeneous application market demand. In other words, if the incumbent battery manufacturers had sufficient industry knowledge and capabilities at the intersection of technological-application market-business model and value chain dimensions, it would have been extremely difficult for the Li-ion battery industry to experience an increasing number of new firm entries. Yet, given the uncertainty residing across multiple dimensions, the industry experienced more new firm entry, which would further suggest that the battery incumbents did not have sufficient industry knowledge that accounted for the intersections between all the dimensions of uncertainty.

Furthermore, there was institutional (i.e., regulatory) uncertainty when the US government passed the Energy Improvement and Extension Act of 2008, which granted tax credits for new qualified plug-in electric vehicles, as well as the American Recovery and Reinvestment Act (ARRA) and the American Clean Energy and Security Act (ACES) that allocated $2.4 billion to support the development of next-generation batteries, electric vehicles, smart grid technology and infrastructure. Through its grant programs, the government not only strove to encourage innovation efforts for clean technology from the supply-side (i.e., advancing Li-ion battery technology), but also to incentivize end-consumers on the demand-side towards the adoption of electric vehicles. Yet, it was not clear how such institutional stimulators would influence innovation in Li-ion battery technology for the electric vehicle market. This was especially true at a time when the electric vehicle market was viewed as a risky play by the incumbent battery manufacturers, such that if Li-ion batteries were handled poorly, it would have severely raised potential legal and reputational liability for battery manufacturers (Kelty, 2020). This implies institutional (i.e., social legitimacy) uncertainty for the Li-ion battery industry that required further knowledge-generation efforts that could have further discouraged the electric vehicle as a potential market.

Actors and firms faced unexpected uncertainty across multiple dimensions – technological, application market, competitive, business model and value chain, and institutional. Such dimensions of uncertainty were not only triggered by the discovery of a new application market for Li-ion batteries but also by the technical challenges that were arising from the well-established consumer electronics market. As actors and firms directed efforts to resolve uncertainty triggered by each application market, especially by the electric market, the Li-ion battery industry had to experience a transformation to account for the expected future demand across multiple application markets that differed in growth rates and scale.

4.2.3 Reconfigured Market: 2013—2023

As previously mentioned, the major Li-ion battery recalls that occurred in the consumer electronics market had directed the efforts of actors and firms towards addressing knowledge gaps across multiple dimensions of uncertainty. But while uncertainty triggered by the consumer electronic application market was reduced for laptops, there was unsettled technological uncertainty in other application markets, such as smartphones and aircraft. For instance, in 2013, Boeing was forced to ground its fleet of 787 Dreamliners due to electrical system problems that were traced to Li-ion battery failure. Furthermore, in 2015, Samsung had to recall approximately 2.5 million Galaxy Note 7 smartphones because of battery failure that caused fires.

Overall, most industry efforts by actors and firms were directed towards addressing uncertainty across its multiple dimensions for applications that had an average of three to six battery cells (e.g., consumer electronics, medical, military). Yet, there was still unresolved uncertainty triggered by other application markets, as in the case of electric vehicles or grid energy storage systems, in which each product contained thousands of battery cells.

It was only around the early 2010s that incumbent battery manufacturers viewed electric vehicles as a potential application market for Li-ion battery technology. By 2012, more traditional automakers commercialized electric vehicles using Li-ion batteries supplied by incumbent battery manufacturers (e.g., Panasonic, LG Chem). Critically, from that point onwards all commercialized electric vehicles used Li-ion battery technology. This implies that industry actors and firms had directed efforts in resolving uncertainty at the nexus of technology and the application market for electric vehicles. Yet, unresolved uncertainty remained at the technological-application market nexus related to the required technical features that would generate mass adoption of electric vehicles, i.e., cost, battery safety, charging time, and range anxiety.

From a mass-production perspective, there was technological uncertainty related to challenges of scaling Li-ion batteries for the electric vehicle market. Such uncertainty was demonstrated in 2012, when US battery producer A123 Systems filed for bankruptcy and was acquired by a Chinese automotive components manufacturer, Wanxiang Group. This battery start-up exit forced the electric vehicle producer Fisker Automotive to suspend its production. For industry sales to take off, the generated industry knowledge and beliefs had to incorporate interactions across multiple dimensions of uncertainty while considering both scalability and cost effectiveness (Moeen et al., 2020). Attending to scalability is not only about producing and delivering more of the same product, but also about efforts in broadening the industry's appeal to a wider market scope (Moeen et al., 2020).

In addition, there was considerable competitive uncertainty triggered by the application market uncertainty for electric vehicles. As the demand for electric vehicles evolved, there was also an increase in the number of new firm entries. Although the Li-ion battery industry did not experience a technological disruptive change, it was not clear how the incumbent industry would address such application market demand. An increase in new firm entries could imply that incumbent battery manufacturers (e.g., Sony, Panasonic) did not have the same market dominance as they had during the Preliminary Market Era. Thus, opportunities arose not only for new firm entry, but also for other existing battery manufacturers to strive for market leadership.

Although technological uncertainty was reduced, in terms of using laptop Li-ion battery technology for electric vehicles, battery manufacturers faced considerable uncertainty in terms of the business model value chain that will meet the future demand in the electric vehicle market. Other than the company Build Your Dream (BYD), no incumbent battery manufacturer had downstream capabilities in the electric vehicle application market. Since the electric vehicle market was in its emerging stages, it was unclear what would be the dominating business model, i.e., supplier-partnership (*supply*), alliance (*ally*), or vertical integration (*make in-house*). Hence, addressing the critical uncertainty associated with business models and value chain activities would not only ensure a sustainable mode of value creation and value capture, but also accommodate the scale of demand in consumer electronics and electric vehicle markets. By 2017, the Li-ion battery industry experienced another sales takeoff driven by the demand from the electric vehicle market.

Yet, there remains considerable institutional uncertainty regarding the policies or programs that would accelerate the domestic development of Li-ion battery technology. For instance, in 2021 the Federal Consortium for Advanced Batteries issued a National Blueprint for Lithium Batteries. This blueprint lays out the goals and actions to guide federal agency collaborations to achieve long-term economic competitiveness over the Li-ion battery value chain. However, as shown in Figure 2-1, the electric vehicle market accounts for more demand for Li-ion batteries than does the consumer electronics market. This implies that actors and firms had directed considerable efforts in addressing uncertainty across multiple dimensions.

4.3 Possible explanations

In this section, I elaborate on and evaluate the predictions of the prevailing theories of IE, Disruption, and MT in explaining dimensions of industry evolution observed in the evolution of the Li-ion battery industry (see Table 2-1 for summary of findings). I do so by considering the Li-ion battery as an electrochemical storage device embedded within the technological system of downstream end-products (e.g., laptops, electric vehicles).

[Table 2-1 about here]

4.3.1 Industry Emergence

If IE is the best possible explanation to the empirical puzzle, then we would observe a linear trajectory of incubation, firm takeoff, and sales takeoff, and the temporal periodization is based on those industry milestones (Gort & Klepper, 1982; Agarwal & Bayus, 2002; Moeen et al., 2020). Such an *instance of emergence* and linear trajectory can be observed in Figure 2-3, which illustrates the application market demand trajectory (measured in kWh) for Li-ion batteries in consumer electronics since the Li-ion battery was first commercialized in 1991. During the 15 years following the first commercialization, the actual demand for Li-ion batteries was primarily driven by the sales in the consumer electronics market. More specifically, by zooming-in on the sales trajectory, it shows that the initial sales takeoff milestone for the Li-ion battery industry occurred in 1995. This suggests that industry actors and firms reduced considerable uncertainty across multiple dimensions – i.e., technological, application market, competitive, business models and value chain, and institutional – and optimized industry knowledge for scaling batteries for the consumer electronics market. In other words, the nature of uncertainty decreased over time since “sales-takeoff milestone is often hailed as the turning point between the nascent and embryonic state of an industry and its established growing state” (Moeen et al., 2020, p. 235).

[Figure 2-3 about here]

Similarly, by considering the electric vehicle market as another *separate instance of emergence*, Figure 2-4 illustrates the application market demand trajectory (measured in kWh) for the electric vehicle market. By 2017, the Li-ion battery industry experienced another instance of sales takeoff by demand in the electric vehicle market. This illustrates that, since its first commercialization, the Li-ion battery industry has experienced two instances of sales takeoff across different application markets. Yet, the IE framework would predict a single instance of sales takeoff and does not explain the process of multiple instances of sales takeoff.

[Figure 2-4 about here]

Each application market (i.e., consumer electronics, electric vehicles) consists of a hierarchy of sub-technologies that meets a purpose in accordance with the purpose of the entire technological system (Arthur, 2007, 2009; Goldfarb & Kirsch, 2020). Thus, the breadth of complementarities (i.e., sub-technological solutions) and their recombination within each technological system only developed over time. Thus, by assuming that the Li-ion battery technology for the electric vehicle market was simply a continuation process of the emergence of the Li-ion battery industry, we would overlook the increasing nature of uncertainty triggered by the application-related market demand shock (i.e., following the introduction of the Tesla Roadster in the electric vehicle market) and innovative efforts by actors and firms associated with the observed evolutionary trajectories. It would be assumed that the process of scaling the production of Li-ion batteries from the consumer electronics market to the electric vehicle market was unproblematic. In fact, such an assumption is represented in Figure 2-5 when mapping the emergence and evolution of the Li-ion battery industry to the IE framework. The black line resembles the approximated actual global demand (measured in kWh) for Li-ion batteries. The gray bars represent the yearly number of new entrants by US-based battery start-ups. The evolutionary trajectory in Figure 2-5 implies that the level of uncertainty is linearly decreasing over time as industry actors and firms generate and aggregate industry knowledge and beliefs across multiple dimensions of uncertainty (i.e., technology, demand, ecosystem, institutions). In particular, the uncertainty at the technology-demand nexus is more salient during the incubation stage and less salient throughout the post-commercialization stages. Lastly, in terms of the competitive landscape under the IE framework, we would observe a shakeout or consolidation among firms amid sales growth.

However, in this context, I observe that the impact of the significant application-related market demand shock triggered uncertainty across multiple dimensions in an unexpected way. Such uncertainty triggered by the electric vehicle market was strategically critical to actors and firms in the industry. In particular, the uncertainty at the technology-demand nexus was salient during the incubation stage and post-commercialization, which necessitated actors and firms to revisit the uncertainty across multiple dimensions. Furthermore, I have observed more than one instance of sales takeoff and a new wave of new firm entry amid sales growth.

Therefore, I conclude that the IE explanation is inconsistent with what I observe in this context. Brief boundary conditions to follow from using the IE framework when I map the evolution of the Li-ion battery industry to the proposed MT framework.

[Figure 2-5 about here]

4.3.2 Disruption

If the classical Disruption model (i.e., Christensen, 1997) is our best possible explanation to the empirical puzzle, then we would expect a discontinuous trajectory – i.e., a transition from Li-ion battery to some novel battery chemistry or other technological system – and the temporal periodization would be based on the point of a new technological regime. The nature of uncertainty is assumed to decrease over time, in which it is high in the event of a new technology and decreases as the improvements in the price-performance of the technology matures. We may observe a demand shock if incumbents are overshooting customer needs and are blind-sided by innovations of new entrants. The possibility of new firm entry amid sales growth would depend on the impact of the new technology (or market) on incumbent scaling capabilities, i.e., competency-enhancing versus competency-destroying (Tushman & Anderson, 1986). If incumbents can satisfy demand, it would increase barriers for new firm entry. Lastly, instances of sales takeoff would be unexplained under a Disruption-based model.

However, in the evolution of the Li-ion battery industry, I observed that the same base principles of a Li-ion battery cell used previously for laptops were used for the consumer electric vehicle (Tesla Roadster), but on a significantly larger scale – i.e., while the laptops commonly required six battery cells, the Tesla Roadster required

6,831 similar battery cells. Notably, the difference in scale of batteries required in the electric vehicle did not render the capabilities of incumbent battery manufacturers obsolete nor were they disrupted by the increasing number of new entrants. The application-related market demand shock necessitated incumbents to reconfigure their scaling capabilities of producing Li-ion batteries for the electric vehicle market. In other words, the incumbent battery manufacturers needed to revisit the current system design in terms of mass-producing Li-ion batteries to meet the expected future demand for Li-ion batteries across different application markets. Therefore, I conclude that this explanation is unsupported in this context.

4.3.3 Market Transformation

If MT is the best possible explanation to the empirical puzzle, then we would observe a non-linear evolutionary trajectory, in which the temporal periodization is context-specific. Following the emergence of a new technology in a new application market, the nature of uncertainty would decrease over time and then increase when the application of the same technology expands into a different application market. Such an unexpected rise of uncertainty is triggered by a significant demand shock. In terms of the competitive landscape, we would observe an increasing number of new entrants amid sales growth. Lastly, we can observe more than one instance of sales takeoff.

In fact, by mapping the evolution of the Li-ion battery industry to the proposed conceptual framework of MT (as illustrated in Figure 2-6), we would be able to broaden the lens of IE that occurred for Li-ion batteries in the consumer electronics market. In so doing, we would observe the waves of new firm entry after the initial sales takeoff. In addition, we would observe the instances of sales takeoff across different application markets (i.e., first in consumer electronics and then electric vehicles), and an application-related market demand shock that triggered increasing uncertainty across multiple dimensions that were expected to have been resolved prior to the industry's initial sales takeoff. This suggests that uncertainty at the nexus of technology and demand is not only salient during the incubation stage but also post-commercialization, which necessitated actors and firms to revisit other dimensions of uncertainty, such as competitive, business model and value chain, and institutional. The proposed MT framework revealed that the application-related market demand shock shaped the insignificance of the industry's initial sales takeoff that initially occurred in the consumer electronics market. Such a critical instance of industrial change would have been understudied using the IE framework.

[Figure 2-6 about here]

Some theories on market evolution have shown that an industry could experience a new wave of firm entry when a new generation of the underlying technology expands into a new market. For instance, using data from the laser industry, Klepper and Sleeper (2005) show that the industry experienced a new wave of firm entry when laser technology was introduced in a new application market. Whereas Franco et al. (2009), using data from the disk drive industry, have shown that the industry experienced a new wave of firm entry when a smaller generation of disk drive was introduced in a new market. Such prior studies tend to associate the process of market transformation (i.e., market expansion) to simply a new demand application: a trivial process of changing the form factor (i.e., incremental innovation) of the focal technology (e.g., reducing the size of the technology in the disk drive industry) or simply changing a component (i.e., modular innovation) in the current system design to satisfy the demand in a new application market. However, the market transformation in the Li-ion battery industry is a non-trivial process due to the nature of the Li-ion battery technology and its applications. It is about the interdependencies of the battery system design for different application markets (i.e., consumer electronics versus electric vehicles), the base principles of the Li-ion battery technology used for each application (Arthur, 2009), and the uncertainties that were triggered by each application market. In other words, the same base principles, at the battery cell-level (i.e., current technology trajectory), used for laptops were used for electric vehicles. However, it is difficult to enact the same base principles, at the current system design-level, when battery manufacturers tried to mass-produce a chemical storage device – i.e., Li-ion batteries – for different application markets that triggered different challenges of scaling and dimensions of uncertainty. Therefore, the process of market transformation necessitates examining the current technology trajectory in conjunction with the current system design and uncertainties triggered by different emerging markets. For instance, Figure 2-7 demonstrates that while the same base principles of the Li-ion battery technology (i.e., battery cell and its components) were used for laptops and electric vehicles, the magnitude of engineering problems, breadth of technological complementarities, and challenges of scaling were different for consumer electronics versus electric vehicles.

[Figure 2-7 about here]

By zooming-in on the industry dynamics during the period of Resurfacing Uncertainty (see section 4.2.2 Resurfacing Uncertainty for detailed contextual evidence), I demonstrate how the application-related market demand shock triggered increasing uncertainty across multiple dimensions. In terms of uncertainty at the application market and technology nexus, industry experts did not believe that using laptop batteries for electric vehicles was a viable solution because connecting 7,000 battery cells and electronically monitoring the thermal event of each cell was a great engineering challenge (Berdichevsky, 2021). In addition, expert forecasters were overestimating the size of the EV market and point of sales takeoff that would happen sooner. Such application market and technology uncertainty nexus triggered competitive uncertainty, in which initially incumbent battery manufacturers did not want to sell Li-ion batteries for the electric vehicle market because of safety concerns. If there was any cause of fires due to battery failure, it would raise potential legal and reputational liability. This suggests that incumbent battery manufacturers did not have a winner-take-all advantage as they did in selling batteries to the consumer electronics market, thus, created opportunities for new entrants. In terms of business model and value chain uncertainty, the demand of Li-ion batteries in the electric vehicle market did not render the capabilities of incumbents obsolete. However, the scale of batteries required in electric vehicles was so large that incumbents needed to reconfigure their strategies to meet demand. For example, while Panasonic had an alliance with Toyota and supply relationship with Tesla, BYD vertically integrated and produced cars as well, and CATL transitioned from producing batteries for consumer electronics to electric vehicles. This is critical because, in retrospect, such strategic choices influenced the reshuffling of industry leadership and today (2023) CATL is the largest battery manufacturer for electric vehicles. Lastly, there was institutional uncertainty in terms of funding and policies for developing Li-ion battery technology. Yet, how would those institutional stimulators for battery development achieve the intended goal of high adoption of electric vehicles was not obvious.

By the early 2010s, incumbent battery manufacturers started to view the electric vehicle market as a potential application market because there was an increase in announced commitments by the traditional automakers to commercialize new models of electric vehicles with Li-ion batteries. In fact, by 2010, traditional automakers like Toyota and Daimler considered adopting Tesla’s battery strategy for their new electric vehicles (Bloomberg, 2010). Thus, it may be arbitrary to associate the end of the Resurfacing Uncertainty period and the change in the level of uncertainty with the commercialization of the Tesla Model S. However, the commercialization of the Model S represented an inflection point in the automobile industry. It signified a reduction in the level of uncertainty in terms of using laptop Li-ion battery technology for electric vehicles. In 2013, this vehicle was the first electric car to win the “Motor Trend Car of the Year” award, by all measures, not only among other electric vehicles but also against internal combustion engine vehicles (Yeadon & Mackenzie, 2012). This award signified that Tesla’s architectural battery strategy for electric vehicles was more successful than other battery strategies. In addition, as of 2012, all announced models of electric vehicles by the traditional automakers were going to be using Li-ion battery technology. Thus, if we were to consider a different year to the end of the Resurfacing Uncertainty period and the change in the level of uncertainty, we might bias our analysis in terms of uncertainty across its multiple dimensions in the evolution of the industry, especially at the nexus of technological and application market dimensions.

By examining the dimensions of uncertainty that actors and firms faced in each period after the commercialization of the Li-ion battery technology in potential application markets – first in the consumer electronics market then in the electric vehicle market – I suggest that the critical period of Resurfacing Uncertainty (2006—2012) unfolded potential industry knowledge gaps across multiple dimensions, hence, created opportunities for new firm entry. Therefore, I conclude that MT is the best possible explanation to the observed empirical puzzle in the evolution of the Li-ion battery industry.

5. IMPLICATIONS FOR THEORIES OF INDUSTRY EVOLUTION IN STRATEGIC MANAGEMENT

The deep dive industry analysis revealed that the approaches of both IE and Disruption may be limited in explaining the evolution of the Li-ion battery industry. Although a single-industry study limits the generalizability of the findings, my findings have implications for theories of industry evolution in Strategic Management.

5.1 Interdependency of technology trajectory, system design, & dimensions of uncertainty

Industry evolution has been extensively studied through streams of research in evolutionary economics (Gort & Klepper, 1982), technology management (Abernathy & Utterback, 1978; Tushman & Anderson, 1986; Christensen, 1997), and organizational ecology (Hannan & Freeman, 1977). The stages of the industry are characterized by the patterns of producer firm entry and exit. In general, the emergence stage depicts entry by a small number of firms, followed by an acceleration in firm entry during the growth stage, then a sharp exit in firms during the shakeout stage, and an eventual mature stage characterized by a stable number of firms with low levels of entry and exit (Gort & Klepper, 1982). Evolutionary studies have associated the observed patterns of the industry life cycle with different explanations. For instance, in evolutionary economics, external knowledge leveraged by entrants is a critical determinant for firm entry (Gort and Klepper, 1982), while technology management scholars have associated patterns of industry evolution with technological changes, in which the patterns of firm entry and exit are influenced by technology cycles (Abernathy & Utterback, 1978; Tushman & Anderson, 1986; Adner & Kapoor, 2016). On the other hand, organizational scholars have associated the evolution of industries with the density of firms and its implications on the forces of legitimization (Hannan & Freeman, 1977; Sine & Lee, 2009).

Building on the seminal evolutionary studies, more recently, scholars have documented cases in which efforts in building industry knowledge base and beliefs precedes the instance of a product's first commercialization, also known as the incubation stage, which is triggered by scientific discoveries, unmet user needs, or mission-oriented grand challenges (Forbes & Kirsch, 2011; Moeen & Agarwal, 2017; Agarwal, Kim, & Moeen, 2021). The incubation stage is characterized by high uncertainty across multiple dimensions, and efforts in building industry knowledge and beliefs by actors and firms have critical implications for the post-commercialization evolutionary stages of the industry (Kirsch et al., 2014; Moeen, et al., 2020). Studies of IE often describe the temporal progression of a potential industry in terms of linear stages of industry incubation, pre-firm takeoff, and pre-sales takeoff by which the industry transition to reach robust commercial activity (Agarwal & Bayus, 2002; Moeen & Agarwal, 2017; Moeen et al., 2020). Of course, not all industries exhibit a smooth linear progression toward commercial viability and robust growth (See Agarwal et al., 2022 for papers in AOM 2022 proceedings: The case of Telecommuting; Rise & fall of Concorde; US Solar Photovoltaic Industry; 3D-Printing Industry).

Scholars studying the emergence and evolution of a given industry have drawn on the IE framework to document the efforts that chart evolutionary trajectories across a variety of industry contexts, such as the Solar Photovoltaic (Kapoor & Furr, 2015), Agricultural Biotechnology (Moeen & Agarwal, 2017), Air Taxis (Zuzul & Tripsas, 2020), Global Mobile Money (Wormald et al., 2021), Bionic Prosthetics (Kim, Agarwal, & Goldfarb, 2022), Drones (Shermon & Moeen, 2022), and Medical Imaging Diagnostic (Lim, Kim, & Agarwal, 2022) industries. In so doing, most IE studies have studied industries that did not exhibit market transformation or have right-censored the timeframe of their study before the onset of market transformation. Thus, those studies have missed market transformation as a feature of industry evolution, in which uncertainty comes back in a way that was not supposed to happen in the traditional industry life cycle model. Furthermore, studies using the IE framework commonly have a one-to-one correspondence between the focal technology and industry context. Thus, failing to consider the interdependencies between the nature of technology, system design, and the dimensions of uncertainty in the process of market transformation, strategy scholars can fundamentally underestimate the nature of complexities (e.g., market size, challenges of scaling, preferences in technical attributes, breadth of technological complementarities) faced by actors and firms when a technology expands into different application markets. This is critical because the entrepreneurial actions by those actors and firms in resolving those complexities fundamentally shape the evolutionary trajectory of the industry.

I suggest that the MT framework broadens the lens of the IE framework when accounting for the emergence of multiple application markets for a GPT. For instance, using the MT framework, I was able to broaden the analysis of the evolution of the Li-ion battery industry beyond the initial instance of sales takeoff. The MT framework revealed that the industry shock triggered by the application market of electric vehicles was so large that the incumbent industry was incapable of responding to the increase in demand. I refer to this process as *super-scaling*. Such application-related market demand shock had triggered a high level of uncertainty across multiple dimensions. This is an important gap because the prevailing theories of IE do not account for unanticipated, systemic shocks that occur after the industry's initial sales takeoff. I suggest when that happens, it can result in a different process called *Market Transformation*.

To better understand how actors and firms engaged in the process of uncertainty reduction associated with evolutionary stages of the industry, I build on recent studies that move beyond aggregating the nature of uncertainty as binary (i.e., *high* during emergence and *low* during maturity) to explicitly distinguishing the dimensions of uncertainty associated with an emerging industry, market, or technology (Goldfarb & Kirsch, 2019; Moeen et al., 2020; Kapoor & Klueter, 2021). Such dimensions of uncertainty can be decomposed as technological, application market, competitive, business model and value chain, and institutional (i.e., social legitimacy and regulatory). Thus, I suggest that decomposing the dimensions of uncertainty associated with the evolution of the industry would enable strategy scholars to examine firm-level behavior *under a dynamic nature of uncertainty* (i.e., decreasing then increasing) rather than assuming uncertainty linearly declines over time.

5.2 Reconfiguration of industry knowledge & beliefs for scaling

On the other hand, theories of Disruption, which exemplify another type of change in industry dynamics, do account for industry shocks: as points of discontinuity on the technological S-curves. Such theories of disruptive technological change have commonly examined the dynamics of industry structure (i.e., firm entry and exit) from the perspective of incumbent firms who are blind-sided by innovative new entrants (Dosi 1982; Foster, 1986; Christensen & Bower, 1996; Christensen, 1997). In other words, the market structure is defined by the incumbent-entrant dynamics in a competition between the old and new technological regime. Thus, the incumbent firm could either forestall entry by their innovative efforts in the old technological regime or respond radically by leaping to the new technological regime. In the event of such disruptive technological change (i.e., transition from old to new technological regime on the S-curve), incumbent firms that do not leap to the new technology could be left behind and face disruption by those who innovated on the new technological path (Dosi, 1982; Christensen, 1997).

Studies that examined incumbent-entrant dynamics have generated important contributions with regards to the conditions under which incumbents are vulnerable to such a disruptive technological event. For instance, incumbents can be less vulnerable when the major technological discontinuity is competence-enhancing versus competence-destroying (Tushman & Anderson, 1986), or when complementary capabilities are critical (Klepper & Simons, 2000) for systematic or architectural innovations versus modular innovations, i.e., supply-side disruption mechanism (Henderson & Clark, 1990). In contrast, entrants can have a competitive advantage when incumbents are burdened by their rigid cognitive frames and routines (Tripsas & Gavetti, 2000) or overly committed to their existing customers, i.e., demand-side disruption mechanism (Christensen, 1997). However, a transformative market change defined narrowly by incumbent-entrant competitive dynamics between substitute technologies would seem incomplete (Adner & Kapoor, 2010, 2016; Ozcan & Hannah, 2020; Goldfarb & Kirsch, 2020).

In technology management, technological S-curves have become a canonical representation for the technology life cycle and the technology-level competition (Foster, 1986; Christensen, 1997; Adner & Kapoor, 2016). The conventional wisdom of the S-curves framework holds that significant effort in developing a given technology results in slight performance improvements during its early stages that are characterized by high uncertainty. Later, as the technology is better understood (i.e., signaling decreasing uncertainty), development efforts lead to rapid performance improvement until reaching the technological limit, relative to its performance, in the maturity stage. Theories of Disruption (see Gans, 2016 for review) would suggest that the transition of efforts in generating industry knowledge and beliefs from the old to new technological regime can be illustrated by multiple discontinuous S-curves (Foster, 1986; Adner & Kapoor, 2016). Each point of discontinuous technological change, also referred to as a disruptive industry event (Tushman & Anderson, 1986; Christensen, 1997), triggers a high level of uncertainty faced by actors and firms as they transition from the old to the new technological regime. It is as if the point of technology discontinuity conceptually resets, to some extent, the level of uncertainty across its multiple dimensions.

Building on seminal theories of technological change and technology management (Abernathy & Utterback, 1978; Tushman & Anderson, 1986; Henderson & Clark, 1990; Christensen, 1997), recent scholars have highlighted that understanding the change of market structure requires broadening the lens by examining incumbent-entrant dynamics along with the co-innovation efforts by other industry participants – i.e., suppliers, complementors, customers (Adner & Kapoor, 2010, 2016; Hannah & Eisenhardt, 2018; Ozcan & Hannah, 2020).

However, any analysis of business models and value chain development focused on a single product market limits our understanding of how actors and firms engage in (re-)configuring industry knowledge and beliefs for multiple application markets, such as in the case of an industry for a general-purpose technology. This study fills this gap through a proposed framework of market transformation. For instance, in the context of the Li-ion battery industry, the then-emerging electric vehicle market for Li-ion batteries did not render the capabilities of incumbent battery manufacturers obsolete, nor were they disrupted by the increasing number of new entrants and their capabilities. Instead, such application-related market demand shock necessitated incumbent battery manufacturers to reconfigure their scaling capabilities for mass-production of Li-ion battery technology to meet the expected future demand for Li-ion batteries across multiple application markets.

5.3 Demand-side trigger of market transformation

Emerging research on market transformation has provided explanations for how market structure can change. For instance, Pontikes and Rindova (2020) suggests that market transformation "arises from the interplay of structure and agency: constraints in structure motivate future-oriented projections of desirable alternatives, and agency is the choice to engage with these conflicts; imagine, envision, and recombine new actionable schemas; and mobilize resources to enact them" (p.157). The study presents a conceptual framework that deepens our knowledge on how different agentic behaviors (i.e., constructive, temporal, and interactive) can alter the market landscape. Meanwhile, from a firm-level perspective, Ozcan & Hannah (2020) demonstrates the influential role of upstream suppliers on firms' supplier-reconfiguration strategies that can subsequently influence market structure. For example, the scholars studied five large global consumer goods manufacturers and their advertising suppliers and found that when a new technology was complementary (rather than a substitute) to the incumbent technology it required firms to reconfigure their supplier strategies to be able to realize the potential value of the new technology. In the global advertising industry context, market transformation was triggered by a new upstream technology that was complementary (rather than a substitute) to the incumbent technology. Thus, market transformation is a process by which firms reconfigure their existing supplier ecosystem when faced with a new complementary technology.

But contrary to some research on market transformation, in which increasing uncertainty can be triggered by a supply-side mechanism such as introduction of a new complementary technology (Ozcan & Hannah, 2020), in the Li-ion battery industry, the unexpected rise of uncertainty was triggered by a significant demand-side mechanism (i.e., application-related market demand shock). The emerging research of market transformation has provided important insights on how different agentic behavior and firm strategies can transform the market structure. This study of market transformation in the Li-ion battery industry presents a temporally distinct process perspective on how the efforts of actors and firms engaged in reconfiguring industry knowledge and beliefs across multiple dimensions of uncertainty that fundamentally changed the market structure for the Li-ion batteries.

5.3.1 Conjectures

Studying the evolution of the Li-ion battery industry through a Market Transformation framework revealed a variety of questions that I present as conjectures to be explored in future research.

C1: *Application-related market demand shock triggers efforts that reconfigure the evolutionary trajectories associated with the industry, market, or technology.*

Efforts in generating industry knowledge and beliefs are fundamental in the process of reducing uncertainty across its multiple dimensions for an industry to evolve across critical milestones and distinct stages (Kirsch et al., 2014; Moeen et al., 2020). The sales takeoff of an industry is reached when industry participants generate sufficient knowledge and beliefs within and across multiple dimensions of uncertainty (Moeen et al., 2020).

Yet, what are the implications on the dimensions of uncertainty from the discovery process of a new potential application market for the same technology? From a theoretical perspective, the IE framework limits the analysis of the dimensions of uncertainty to a single technology within a single industry context. Thus, it is intuitive to suggest that when an industry reaches critical milestones, it represents significant knowledge-generation efforts in reducing uncertainty. But in the case of the Li-ion battery industry, the uncertainty faced by actors and firms would have been underrepresented if we were to use the IE framework to examine the observed evolutionary industry trajectories. From a practitioner perspective, it would have been impossible at that moment of first commercialization for actors and firms within the Li-ion battery industry to engage in optimizing industry knowledge and beliefs for the electric vehicle market when there was no clear commercial opportunity to pursue. Thus, the industry knowledge and beliefs were optimized for the consumer electronics market since there was a growing demand in such a market but no real demand in the electric vehicle market.

Examining the dynamic nature of uncertainty associated with the evolution of the industry was possible through a market transformation perspective that permits a careful industry analysis by leveraging a systematic periodization of industry events that unfolded over time. The critical element of the market transformation framework is that different dimensions of uncertainty are going to be salient at different times, not only characterized by the critical milestones and emerging stages of an industry (Moeen et al., 2020) but also by considering the significance of an application-related market demand shock.

C2: *After the first commercialization of the industry, triggers of increasing uncertainty can lead to non-linear evolutionary trajectories of firm entry & sales.*

The emerging stages of an industry can be represented by the evolutionary trajectories of firm entry and sales (Gort & Klepper, 1982; Agarwal & Bayus, 2002; Moeen et al., 2020). The IE framework suggests that the acceleration pattern in firm entry occurs before the industry reaches the milestone of sales takeoff. Industries that reach sales takeoff represent a milestone in which industry participants have generated sufficient knowledge and beliefs that incorporate scaling production and cost effectiveness. This implies that much of the uncertainty to scaling production has been addressed, and it would be extremely difficult for new firms to enter the market at this stage. In other words, incumbent firms would be able to satisfy demand by simply scaling units of production; hence, we should expect more sales growth.

Yet, how can increases in new firm entry be explained after the industry has reached sales takeoff? Using the MT framework revealed that the Li-ion battery industry experienced a second wave of new firm entry following the initial sales takeoff. This wave of new firm entry was triggered by an industry shock that was rooted in using Li-ion battery technology in a new market on a significantly larger scale. Thus, when the focal technology expands to new application markets, it can generate an industry shock. In effect, it would increase the level of uncertainty in previously resolved dimensions that would require efforts by actors and firms to (re-)configure industry knowledge and beliefs to consider the nature of scale for the new market demand, precipitating similar entry dynamics to what I observed in the Li-ion battery context.

C3: *Examining the choices of firm strategy in a market transformation necessitates periodization through a historical lens.*

For scholars studying firm strategy under uncertainty (Gans, Stern, & Wu, 2019; Rindova & Courtney, 2020; Furr & Eisenhardt, 2021), using a historical lens to periodize change has strategic implications as it provides more contextual richness in terms of the dimensions of uncertainty faced by firms in the process of choosing their strategy (Pillai, Goldfarb, & Kirsch, 2020).

A key insight derived from periodizing the evolution of the Li-ion battery industry was that in each period, actors and firms (i.e., incumbent battery manufacturers and new entrants) faced different levels of uncertainty associated with each application market. Although firms did not necessarily control the uncertainty of their environment, they controlled whether they choose to participate in it; hence, uncertainty becomes a choice.

The MT perspective has led us to recognize that as the technology within the focal industry becomes applicable across multiple application markets over time, it creates commercial opportunities for new firm entry and multiple waves of sales takeoff *(C2)*. In the case of the Li-ion battery industry, it experienced a transformation to accommodate demand across multiple application markets that scaled along different trajectories. This period of transformation was characterized by high uncertainty across multiple dimensions *(C1)*. Thus, how do new entrants position themselves within the technological system, as their entry strategy? And what market applications do they select into? Answers to these questions provide implications for efforts in (re-)configuring industry knowledge and beliefs as those entrants can infuse cutting-edge knowledge that builds on industry knowledge generated from prior periods.

In the case of the Li-ion battery industry, firms that entered during the MT process of the Li-ion battery industry faced strategic trade-offs in terms of which market to optimize their technology for: the initial consumer electronics market, the emerging electric vehicle market, or both? How would they position themselves within the transformed industry: as upstream component innovators or downstream complementors or system integrators? When and why would they choose a fit-in value chain strategy or a disruptive strategy? Overall, how do new entrants choose their entry strategy when the economic value shifts across application markets?

Thus, by using a MT perspective by periodization, scholars studying the emergence and evolution of an industry would better understand the industry's environment at a given moment while complementing their process of adjudicating among plausible explanations regarding new firm entry and their choice of strategy. In addition, examining the types of new entrants throughout the process of market transformation can have critical implications for reshaping the evolutionary trajectory of the industry.

6. CONCLUSION

The commercial development of the Li-ion battery industry is consequential for the world economy across multiple domains (e.g., decarbonizing transportation and energy sectors, influencing commodity markets and the politics of countries manufacturing automobiles). In addition, the industry is currently (as of 2023) in its growth stage and expected to grow by five to 10 times (in gigawatt-hours, GWh) in the next decade (Wood Mackenzie, 2022). The evolution of this industry is neither an industry emergence nor it is a technology trajectory (i.e., multiple discontinuous technology S-curves) process, but it is a different transforming scaling process. When the Li-ion battery was first commercialized, industry actors and firms thought the Li-ion battery was applicable for the consumer electronics market. However, over time it turned out that the Li-ion battery can be used in different application markets (e.g., consumer electronics and electric vehicles). In strategy research, models of industry dynamics (i.e., IE, Disruption) that explain waves of new firm entry and sales takeoff, corresponds to one-technology, one-industry. However, studying the evolution of the Li-ion battery industry required a different lens than those used in most industry studies because of the nature of the technology and its applications. Actors and firms faced *different levels of uncertainty* based on the evolutionary stage of each potential application market. After experiencing *multiple instances of sales takeoff* – first in the consumer electronics market, then in the electric vehicle market – the industry has evolved into a *second growth stage*. Importantly, the *challenges of scaling* the Li-ion battery technology for each potential application market are different from the other industries that strategy scholars have looked at when studying the emergence and evolution of the industry (e.g., Lasers, Agricultural Biotechnology, Swiss Watches, Air Taxis, Bionic Prosthetic, Solar Photovoltaic, Mobile Money, Drones, Medical Imaging Devices).

Although a single-industry case study may limit generalizability, the analysis reveals useful insights that may be explored across different industry contexts that might experience an application-related market demand shock. Studies of IE and Disruption theory have underscored that, in the context of industry evolution, the nature of uncertainty plays a critical role yet is often *assumed to decrease over time*. On the one hand, by explicitly distinguishing the multiple dimensions of uncertainty, the IE framework demonstrates that uncertainty decreases as the industry progresses across its distinct stages. The framework provides useful insights into how the focus of actors and firms shifts towards addressing different dimensions of uncertainty across time. However, the IE framework does not incorporate *industry shocks* that can trigger *increasing uncertainty* across multiple dimensions that was believed to have been resolved in previous industry stages (i.e., boundary conditions of IE framework). The development process of the "general-purpose" feature of Li-ion battery technology in the electric vehicle market was not simply a continuation of IE. Rather, such applicability resulted in an application-related market demand shock that triggered uncertainty across its multiple dimensions in an unexpected way for actors and firms. Furthermore, examining the evolutionary trajectories using the IE framework would have predicted a firm shakeout/consolidation amid sales growth. The industry would essentially be represented by a single evolutionary trajectory under the IE framework.

On the other hand, the Disruption framework (i.e., discontinuous S-curves) aggregates the nature of uncertainty as a binary state of the world (i.e., *high* during the emergence of a new technology and *low* during maturity stage when reaching technological limits). Thus, the result of discounting the nature of uncertainty in industry evolution models "is a very limited understanding of how actors actually make choices under conditions of uncertainty, and often include strong assumptions about the limitations on reflective action" (Kirsch et al., 2014, p.236).

The findings of this study suggest that approaches of both IE and Disruption are limited in explaining the dimensions of uncertainty associated with the evolutionary trajectories of the industry when the application of the technology expands to multiple heterogeneous application markets over time. In the case of the Li-ion battery industry, the MT framework, which considers a dynamic nature of uncertainty, allowed us to broaden the IE framework in examining the observed evolutionary trajectories and provided a better explanation for the observed multiple waves of new firm entry and more than one instance of sales takeoff in the evolution of the Li-ion battery industry.

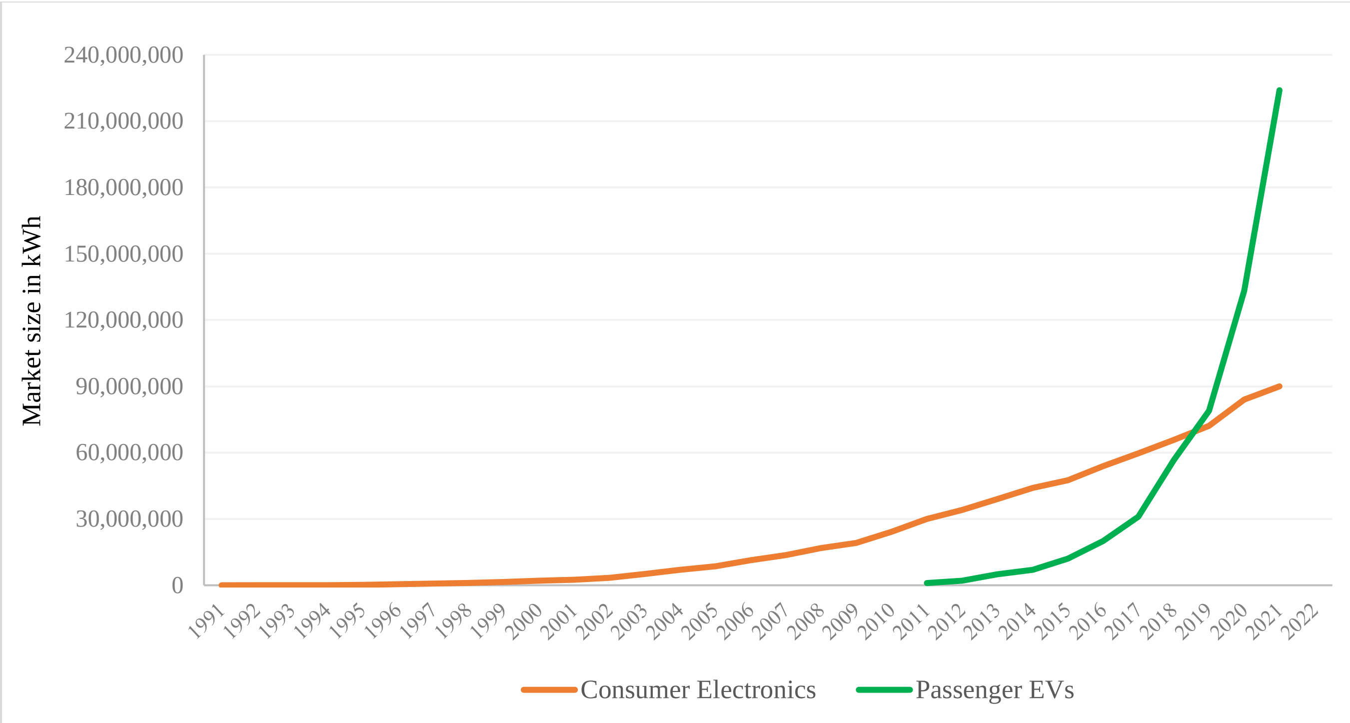

Figure 2-1 Global market demand for Li-ion battery in potential application markets (1991—2022). *Source:* Stringer & Rathi (2020); Stringer & Park (2021); Ziegler & Trancik (2021).

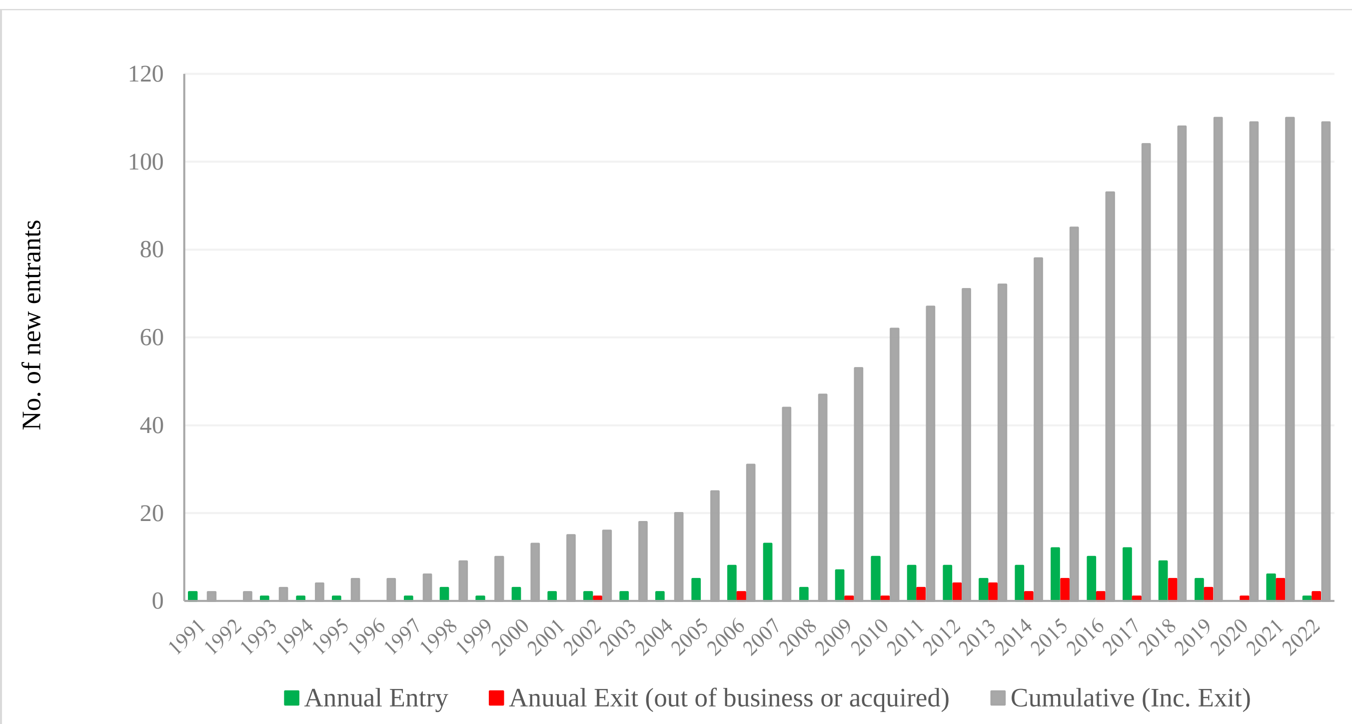

Figure 2-2 US-based start-up entry and exit in the Li-ion battery industry (1991—2022).

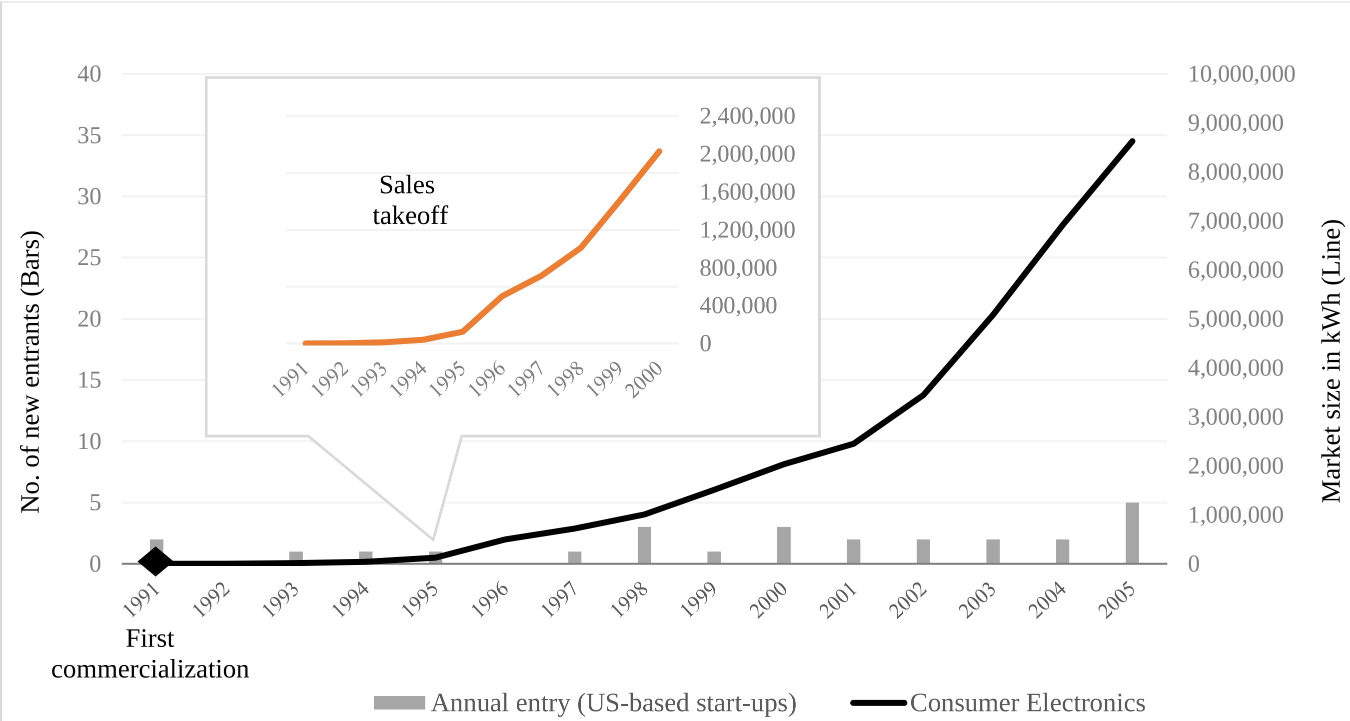

Figure 2-3 Global market demand for Li-ion batteries in the consumer electronics market (1991—2005).

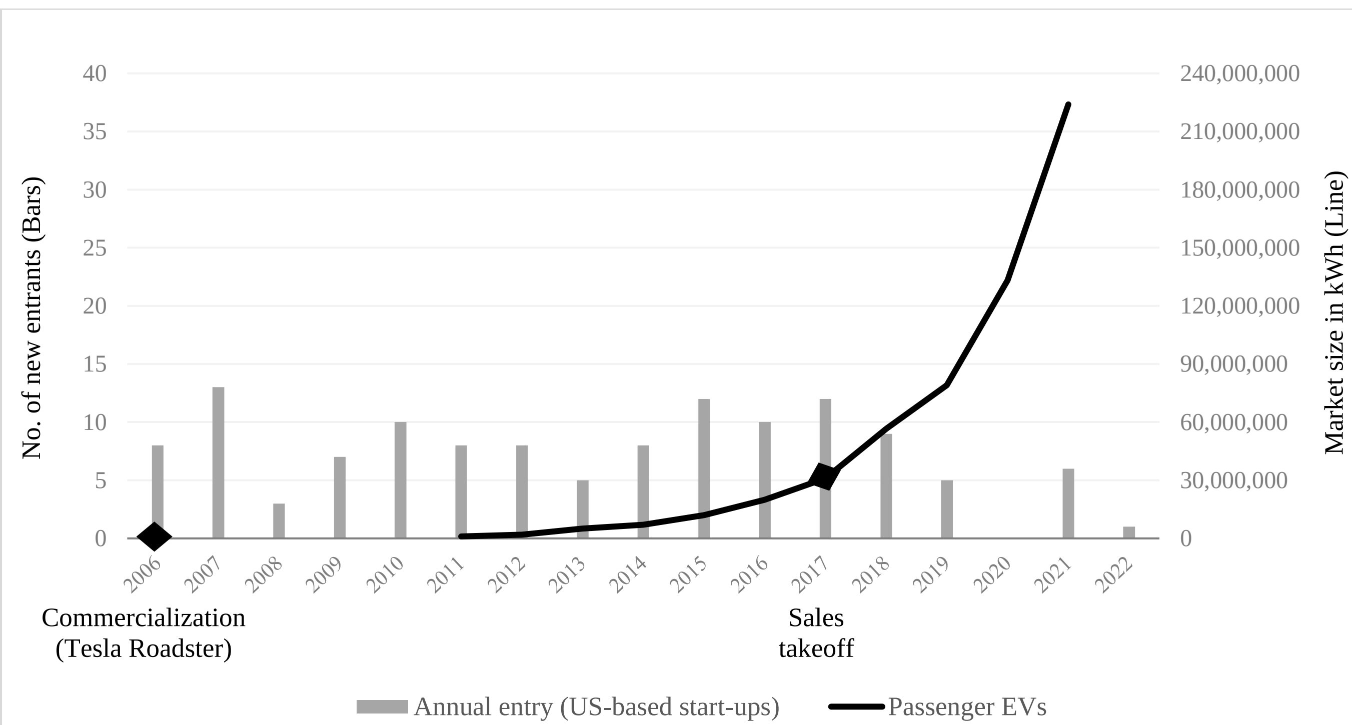

Figure 2-4 Global market demand for Li-ion batteries in the electric vehicle market (2006—2022).

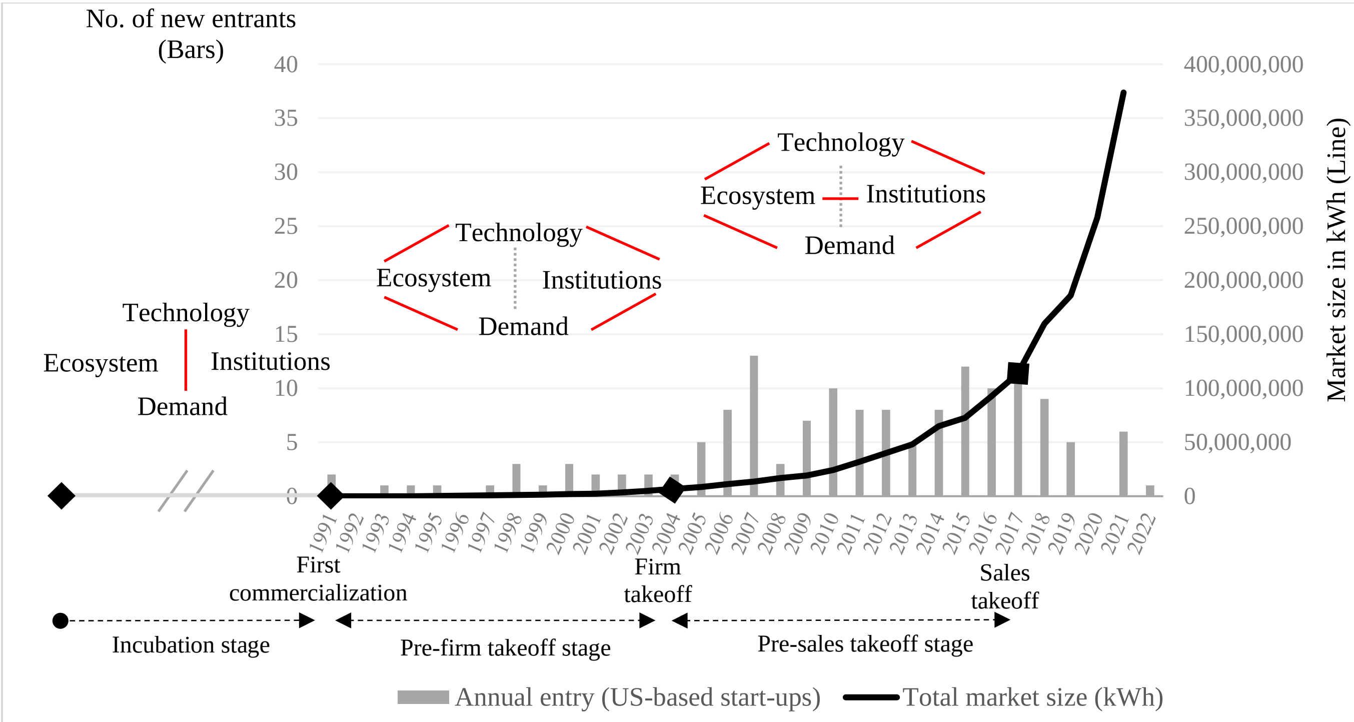

Figure 2-5 Mapping the emergence & evolution of the Li-ion battery industry to the Industry Emergence (IE) framework proposed in Moeen et al. (2020).

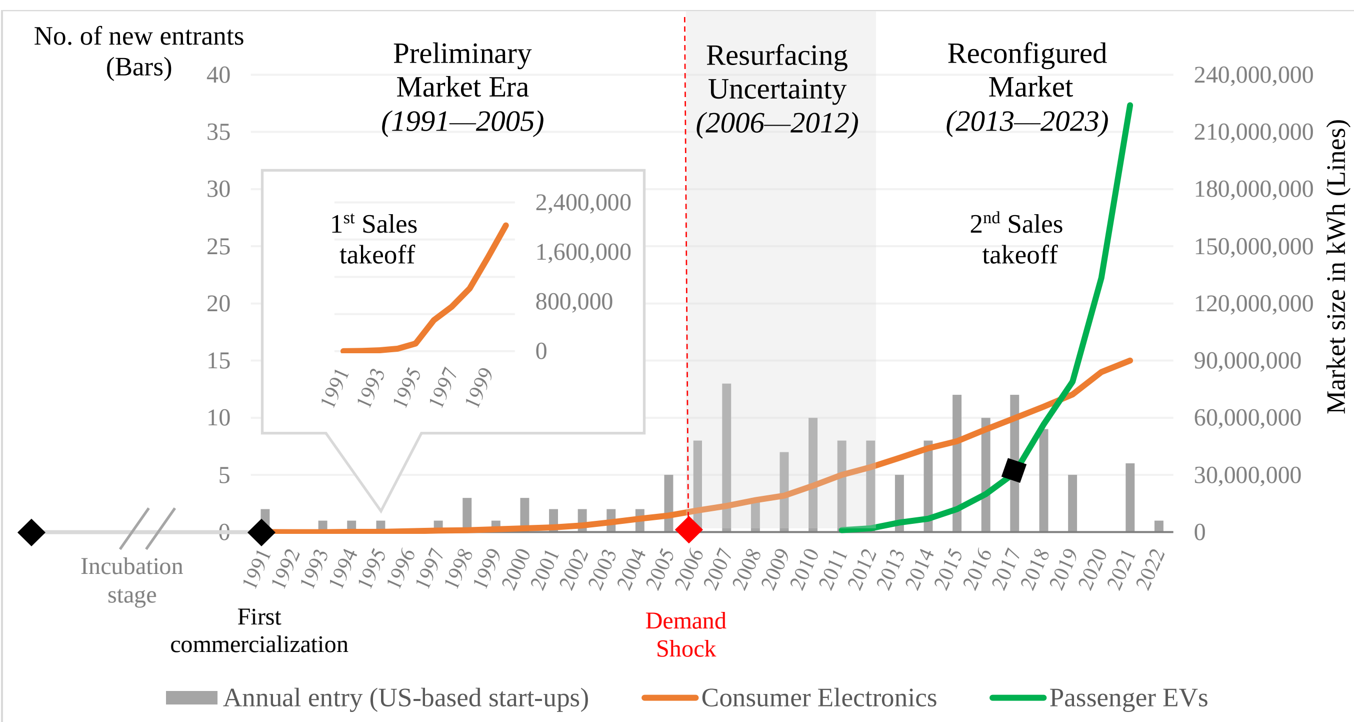

Figure 2-6 Mapping the emergence & evolution of the Li-ion battery industry to the proposed Market Transformation (MT) framework.

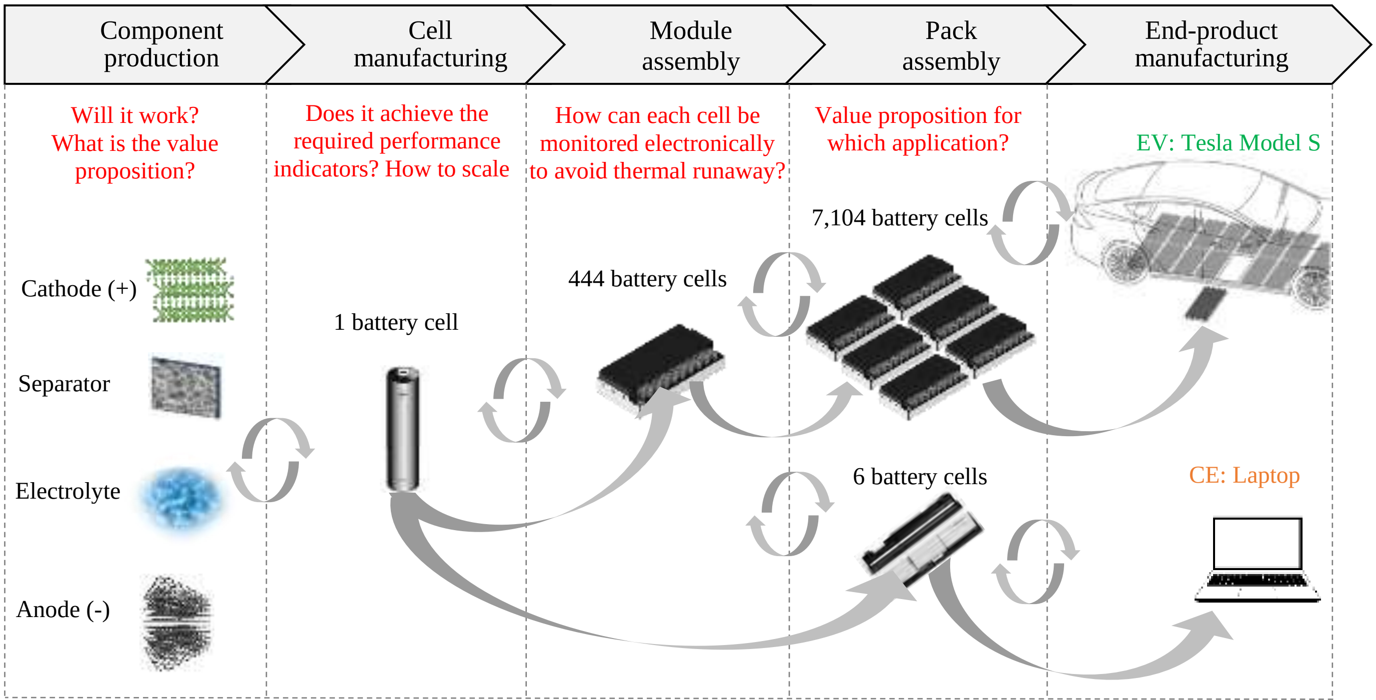

Figure 2-7 Value chain and challenges of producing a battery-cell for different application markets.

Table 2-1 Summary of findings.

Dimensions of uncertainty & industry evolution:	If the Li-ion for the EV market was a **continuation of the emergence** of the Li-ion battery industry…	If the Li-ion battery industry for the EV market is a **market transformation**, this is what it looks like…	If the Li-ion battery industry for the EV market is a **disruptive event**, this is what it looks like…	Evolution of the Lithium-ion Battery Industry
(1) Evolutionary trajectory	Linear (Incubation → Firm takeoff → Sales takeoff)	Non-linear (Context-specific)	Discontinuous (technology S-curves)	Non-linear (Preliminary market era → Resurfacing Uncertainty → Reconfigured market)
(2) Temporal periodization	Based on industry milestones	Context-specific	Based on new technological regime	Context-specific
(3) Nature of uncertainty	Decreases (High-low)	Dynamic (Decreases then increases from a supply-side mechanism: New complementary technology)	Decreases (High-low)	Dynamic (Decreases then increases from a demand-side mechanism: New application market)
(4) Demand shock	No demand shock	Supply-side shock by new complementary technology	Supply-side or demand-side disruptive event (shifting to new technological regime)	Demand-side shock by application-related market demand shock
(5) Uncertainty at technology-demand nexus	More salient during incubation & less post commercialization	More salient during incubation & post commercialization	Salient during early stages post-commercialization of new technology	More salient during incubation & post commercialization
(6) Competition amid sales growth (No. of new entrants)	Shakeout/consolidation	N/A	Shakeout/entry depends on incumbent-entrant dynamics	Increasing entry
(7) Instances of sales takeoff ("Hockey-stick" growth)	Single	N/A	Multiple for each new technological regime	Multiple for the same technology
(8) Value creation and value capture strategies develop around the value proposition of	Single product market	Single product market	Single product market	Multiple heterogeneous product markets
(9) Unit of analysis: Strategic actors (re-)configuring industry knowledge & beliefs	Multiple (actors & firms)	Multiple (actors & firms)	Multiple (actors & firms)	Multiple (actors & firms)
(Goldfarb & Kirsch, 2019; Moeen et al., 2020; Kapoor & Klueter, 2021)	(Gort & Klepper, 1982; Agarwal et al., 2017; Moeen et al., 2020; Struben et al., 2020)	(Pontikes & Rindova, 2020; Ozcan & Hannah, 2020; Goldfarb & Kirsch, 2020)	(Abernathy & Utterback, 1978; Dosi, 1982; Foster, 1986; Tushman & Anderson, 1986; Henderson & Clark, 1990; Christensen, 1997; Adner & Kapoor, 2016)	This study

CHAPTER 3: ESSAY 2

CHOOSE YOUR UNCERTAINTY: ENTREPRENEURIAL STRATEGY IN THE EVOLUTION OF THE LITHIUM-ION BATTERY INDUSTRY

1. INTRODUCTION

This chapter reports on a study of entrepreneurial entry strategies by battery start-ups in the Lithium-ion (Li-ion) battery industry, from its initial commercialization in the early 1990s to the present (2023). Building upon the contextual deep dive industry analysis reported in Chapter 2, this study finds that battery start-ups pursued a range of different entry strategies over the course of more than 30 years in the evolution of the industry. Using a dataset of 151 US-based battery start-ups seeking to enter the Li-ion battery industry, I analyze the start-ups' choices of application market and espoused entrepreneurial strategy, which can be "defined as a particular value creation and value capture hypothesis, and the associated set (or sequence) of partial-commitment choices these hypotheses entail" (Gans, Stern, & Wu, 2019, p. 737).

During the critical period of *Resurfacing Uncertainty (2006—2012)*, I observed that only 16% of start-ups founded during that period pursued a *"*specialization-in-generality*"* strategy; that is, only 16% invested in developing general upstream resources and trying to trade them in downstream markets, rather than to directly enter downstream markets (Conti et al., 2019), while 84% of start-ups pursued alternative entry strategies (in effect, focusing on a particular market segment). This behavior highlights an empirical puzzle: prior research on the micro-foundations of GPTs (using data from the laser industry) hypothesized that firms specialize-in-generality when they lack downstream assets and/or face a broader application market demand (Conti et al., 2019). While all battery start-ups in this study lacked assets in downstream application markets (by definition, they were start-ups with few existing resources and relationships), only a few start-ups chose to specialize-in-generality. Thus, in this study I consider the strategic choice of the application market facing an entrepreneurial firm to seek explanations to the observed empirical puzzle at the firm-level; that is, why in the period of Resurfacing Uncertainty was specializing-in-generality a rare choice?

To infer the best possible explanation for the observed empirical puzzle, I followed an Inference to the Best Explanation (IBE) approach (Goldfarb et al., 2022). First, I collected and analyzed a sample of battery start-ups that were founded across three distinct periods in the evolution of the Li-ion battery industry (as identified in Chapter 2). I document their entry, exit, and their choices of targeted application market and entrepreneurial strategy at entry. Thus, I was able to situate the start-ups in their context and trace their strategic choices as the level of uncertainty associated with each potential application market (and its expected size) changed. Then, by documenting the relationship between start-ups' choices of targeted application market and entrepreneurial strategy, I observed that the start-ups' choices were inconsistent with what we would expect from following research on specialization-in-generality. I observed both a diverse mix of strategies in each period and a changing pattern in the choices of those strategies over time. From the theoretically-informed empirical puzzle, as a point of departure, I engaged in an iterative process, shifting between the context and theory to generate possible explanations (i.e., the "lot"), then evaluated each explanation to infer the "best" explanation (Goldfarb et al., 2022).

The historical record revealed that start-ups entering the Li-ion battery industry post-commercialization of the Tesla Roadster, faced a period of *increasing uncertainty*. During this period, it was not obvious what the size of the electric vehicle market would be and when the market demand trajectory would take off (i.e., commence “hockey-stick” growth). Such uncertainty had critical implications for other dimensions of uncertainty, such as technological, business model and value chain, as well as institutional. By elaborating on and evaluating the list of possible explanations, I arrive at the best explanation: infer that the increasing levels of uncertainty associated with each application market generated *uncertainty profiles* that start-ups selected based on the preferences and beliefs of their entrepreneurs or their investors about the nature of those uncertainties, resulting in different *strategic bets*. In other words, the start-up’s choice of strategy was not primarily dictated by their choice of technology but the change in the level of uncertainty associated with each application market (and its relative size) also triggered different strategic bets.

When I examined how entry strategies vary across the three distinct periods identified in Chapter 2, patterns emerge, suggesting (a) that the level of prevailing uncertainty may influence choice of strategy at entry and (b) that contrary to the predictions of General-Purpose Technology (GPT) studies like Conti, Gambardella, & Novelli (2019), Gambardella, Heaton, Novelli, & Teece (2021), and Kapoor & Teece (2021), choice of strategic orientation with respect to uncertainty may reflect factors other than the pure technological considerations they advance. Thus, I demonstrate that across the three distinct periods, start-ups chose different entrepreneurial strategies as the level of uncertainty associated with varying application markets (and their expected size) changed. In addition, prior research on entrepreneurial strategy has often assumed that application market dynamics interact with the choice of entrepreneurial strategy. In this study, I demonstrate how the application market dynamics interact with the choice of entrepreneurial strategy by the *choice of uncertainty*. It is important to note, the uncertainty was not merely a feature of the application market exogenously imposed upon the start-ups in choosing their strategy, but also a choice. In that sense, battery start-ups choose their uncertainty by selecting their targeted application market at entry.

The choice of uncertainty is accompanied with a host of challenges to commercialize battery technology because battery development is a complex process: it is a highly capital-intensive business that requires long development cycles (i.e., experiments take time to prove the desired performance indicators, such as, cycle life, energy density, charging time, etc.), and it requires highly specialized technical skills and large amounts of funding for operations prior to actual commercialization. Adding to the complexities of developing lab-scale battery technology, the choice of an application market to target presents battery start-ups with a different set of sequential challenges to scale. Importantly, the challenges of scaling for the global Li-ion battery market are different from the other industries (i.e., Lasers, Agricultural Biotechnology, Swiss Watches, Air Taxis, Bionic Prosthetic, Solar Photovoltaic, Mobile Money, Drones, Medical Diagnostic Imaging Devices) strategy scholars have looked at when studying firm strategies for value creation and value capture. Therefore, faced with both *application market-related uncertainty* and firm-level challenges, battery start-ups had to make a strategic choice regarding their targeted application market that differed in size, scale of batteries required per product, and level of certainty.

The commercialization of the first mass-produced consumer electric vehicle with Li-ion battery technology the Tesla Roadster in 2006 – was a proof-of-concept that demonstrated the possibility of generating commercial value from an electric vehicle using laptop Li-ion batteries. Although the successful commercialization of this proof-of-concept vehicle increased expectations for growth opportunities associated with Li-ion-based batteries, the shock of the Tesla Roadster also triggered a period of *increasing uncertainty*. For instance, would the Li-ion battery architecture that had become commonly used for consumer electronics also become the standard for electric vehicles? Would the value chain activities that had evolved to serve the consumer electronic-facing Li-ion battery market migrate to serve the automobile industry, or would new business models be needed to support the scale of demand anticipated to come with the growth of mass electrification using Li-ion batteries? Would existing Li-ion battery manufacturers scale to meet forecast demand, or would the electric vehicle market support new entrants, and if so, what kind of start-up strategy would increase the likelihood of success? Looking across the multi-decade history of the Li-ion battery industry, every battery start-up that entered the industry had to choose from a set of possible application markets for their battery technology. Such strategic choice fundamentally influenced the start-up's *path of uncertainty* to commercialization.

This study contributes to strategy research on entrepreneurial strategies for GPTs in the following way. First, for entrepreneurial firms, a technology with a broad market appeal presents tremendous value creation and value capture opportunities as it gets adopted across multiple application markets (i.e., degree of technology generality) over time because it expands their choice set of application markets to target (Conti et al., 2019; Gans, Kearney, Scott, & Stern, 2021). Such technology has been referred to as "General-Purpose Technology (GPT)," "Junior GPT," or "Enabling Technology" (Bresnahan & Trajtenberg, 1995; Teece, 2018; Conti et al., 2019; Kapoor & Teece, 2021; Goldfarb, Taska, & Teodoridis, 2023). Examples of GPTs are found in different industry contexts, including Semiconductors (Bresnahan & Trajtenberg, 1995), 3G/4G wireless (Teece, 2018), Lasers (Conti et al., 2019), Artificial Intelligence (AI) algorithms, 3D-Printing, and Nanotechnology (i.e., engineered silicon). However, the commercialization of Li-ion battery technology, like other GPTs (i.e., semiconductors, electricity, lasers) was not born "general-purpose", but rather its widespread economic impact occurred over a protracted length of time (Bresnahan & Trajtenberg, 1995; Bresnahan & Gambardella, 1998; Goldfarb, 2005; Teece, 2018; Kapoor & Teece, 2021).

Battery start-ups that chose to develop the same technology (i.e., Li-ion battery component or cell) and tried to commercialize their battery technology faced different levels of uncertainty based on their time of entry and choice of targeted application market. Yet, some studies on the micro-foundations of GPTs have generally aggregated the nature of uncertainty. For instance, when scholars examine firms' strategic choices for value creation and value capture, it is commonly assumed that when industry is first commercialized, the early stage is characterized by high uncertainty then followed by decreasing uncertainty over time, or it is assumed that there is no uncertainty in the mature industry stages since the generality feature of the technology is given (Conti et al., 2019; Wormald et al., 2021). In so doing, studies have implicitly assumed that the uncertainty associated with each choice of targeted application market is unproblematic. From an entrepreneurial strategy perspective, by focusing primarily on the entrepreneurial strategies for a GPT in the absence of uncertainty, we lack a systematic analysis of how entrepreneurial strategies are influenced by not only firms' technological capabilities and an increase in the breadth of demand but also by the level of uncertainty associated with the application market they choose to target.

Second, prior research on Specializing-in-Generality has implied that both incumbent and younger entrepreneurial firms (i.e., start-ups) are faced with the same set of strategic choices, i.e., specialize in developing general upstream components, vertically-integrate to specialize in producing downstream products, or do both (Conti et al., 2019; Gambardella et al., 2021). However, in the Li-ion battery industry, while a specializing-in-generality strategy was observed to be pursued by battery start-ups, I document that its dominance as a choice of strategy changed over time. Importantly, no battery start-up in this context was able to specialize in developing a general upstream battery technology and vertically-integrate to produce products in downstream markets (i.e., boundary condition of the specializing-in-generality theory).

Third, while prior research has provided useful insights on when and which firms are likely to specialize-in-generality during the emergence and mature stages of the industry, this study provides more granularity to the changing patterns of choices of entrepreneurial strategies (i.e., including a specializing-in-generality strategy) throughout the evolution of the industry: from its first commercialization in a particular application market to its widespread adoption across different application markets.

To proceed, in section 2, I describe the context of the study by providing a contextual description of the uncertainty that was strategically relevant to battery start-ups across the three distinct periods in the evolution of the Li-ion battery industry (identified in Chapter 2). In section 3, I describe the data sources that enabled me to document the entrepreneurial entry strategies across the three distinct periods and then highlight the observed empirical puzzle. In section 4, I elaborate on the possible explanations (i.e., the "lot") for the observed choices of entrepreneurial strategies selected by battery start-ups. To infer the best explanation, I evaluated the lot to eliminate possible explanations. Then, in section 5, I discuss the generalizability of the findings and where else might we observe similar industry dynamics in which the generalizability of the findings can be assessed. In section 6, I provide the implications for strategy research on entrepreneurial strategies for GPTs under uncertainty and provide possible predictions as conjectures for future research avenues. Lastly, in section 7, I summarize the key findings and contributions, discuss possible limitations, and conclude.

2. CONTEXT & TIMELINE: UNCERTAINTY & ENTREPRENEURIAL STRATEGIES IN THE LI-ION BATTERY INDUSTRY

According to the findings in Chapter 2, the Li-ion battery industry has transformed into an industry that supplies battery technology for multiple application markets: consumer electronics (e.g., camcorders, laptops, cell phones), automotive (i.e., hybrid and plug-in electric vehicles), aerospace, marine, medical, industrial, telecommunications, and large-scale grid energy storage systems. However, the uncertainty associated with each application market (i.e., consumer electronics versus electric vehicles) varied across the three distinct periods in the evolution of the industry.

To understand how uncertainty influenced start-ups in choosing their entrepreneurial strategy, I first document a contextual description of the uncertainty (across multiple dimensions) faced by start-ups choosing their entrepreneurial strategy across the three distinct periods in the evolution of the Li-ion battery industry.

2.1 Contextualizing uncertainty critical to battery start-ups in each period

2.1.1 Uncertainty in the Preliminary Market Era

Shortly after the Li-ion battery technology was first commercialized by Sony for its camcorder in 1991, the sales for Li-ion batteries took off (i.e., "hockey-stick" growth) in 1995, alongside the demand for consumer electronic products such as laptop computers and cell phones. In fact, by 1998 approximately 90% of all laptop computers used Li-ion battery technology. Cellular phones were considered as the subsequent fastest growing application market, which was expected to grow from $145 million in 1997 to $1,726 million in 2002, a CAGR of 64% (Shepard & Brush, 1998). Furthermore, the global market demand for Li-ion batteries (as shown in Figure 1-1 in Chapter 1) outpaced the demand for incumbent battery technologies (i.e., nickel-cadmium – NiCd, and nickel-metal hydride – NiMH) primarily because of its key technical characteristics, such as energy density, power, and cycle life. The sales takeoff for Li-ion battery technology in the consumer electronic market suggests that considerable uncertainty of using Li-ion battery for consumer electronics was reduced. However, using Li-ion battery technology in the application of an electric vehicle was notionally possible and was thought of as something that would happen in the distant future because it required further development. In other words, the short-term uncertainty of using Li-ion batteries for electric vehicles was arguably low because there was a high degree of confidence that there was no market for Li-ion batteries for electric vehicles. For example, in 1996, a forward-looking assessment of advanced battery technologies for electric vehicles prepared by the California Air Resources Board (CARB) concluded that “Lithium-ion will require the greatest time to develop and may not be available until 2005” (Mader, 1996, p. 149).

From an entrepreneurial strategy perspective, the historical record revealed that battery start-ups that entered during the early period of the industry evolution (1991-2005) faced a *decreasing level of uncertainty* in terms of demand for Li-ion batteries in the consumer electronics market. In fact, consumer electronics was the most desirable application market because it had a growing market trajectory. In contrast, a start-up that entered during this period and tried to commercialize a Li-ion battery technology for the electric vehicle market was considered as an ambitious and risky choice (i.e., big innovation bet) because (a) Li-ion battery technology was far from being considered as a viable choice of battery technology by the experts in the battery industry and by most of the traditional automakers in the auto industry, primarily due to its high cost and unresolved technical challenges, and (b) the private market (i.e., venture capitalists) would not have invested in technologies that were not going to be ready for a decade. Access to capital was especially important because developing and commercializing battery technology was a highly capital-intensive business that, even at that time, required approximately between $80 and $250 million (Mader, 1996).

2.1.2 Uncertainty in the Resurfacing Uncertainty

By the early 2000s, technology pioneers at AC Propulsion, a start-up that developed electric powertrains, had developed an electric vehicle prototype (t-zero) that initially used lead acid batteries (Brooks & Gage, 2000), and then used laptop Li-ion battery technology. The development of the t-zero motivated serial entrepreneurs to found Tesla Motors and commercialize the first mass-produced electric vehicle – Tesla Roadster in 2006 – that used Li-ion battery technology. From an entrepreneurial strategy perspective, the commercialization of an electric vehicle that used Li-ion battery technology had expanded the start-ups' choice set of application markets to target. While the prospect of a product that depended on thousands of battery cells would be a valuable opportunity to any battery supplier, the uncertainty of using laptop Li-ion battery technology for the electric vehicle market was fundamental and took several years to be resolved. Thus, battery start-ups that entered during the second period (2006—2012) faced an *increasing level of uncertainty* that was triggered by the successful commercialization of consumer electric vehicles (i.e., industry demand shock of the Tesla Roadster). The architectural battery system for the Tesla Roadster consisted of 6,831 Li-ion battery cells, like those used for laptops in the consumer electronics market. At the same time, most battery experts agreed that such a battery strategy was not a viable solution for the electric vehicle market, especially when considering the significant safety concerns. There were catastrophic Li-ion battery failures and product recalls in the established consumer electronics market because those batteries were not thermally stable and caused fires. Such uncertainty was exacerbated when incumbent battery manufacturers (i.e., Sony and others) forced consumer electronic producers to recall their laptops due to catastrophic battery fire incidents. It further discouraged incumbent battery manufacturers from supplying Li-ion batteries to automakers developing electric vehicles. While the technical failure of the Li-ion battery in laptops triggered technological uncertainty in the consumer electronics market, the uncertainty associated with such an application market was still lower than that associated with using Li-ion battery technology for the electric vehicle market, given that the demand for Li-ion battery technology in the consumer electronics market maintained a steady growth trajectory.

As the size and scope of application markets for Li-ion battery technology were expected to significantly increase (based on ambitious demand forecasts for electric vehicles), there was an influx of private (i.e., venture capital) and public (i.e., grants) funding for advancing Li-ion battery technology. In fact, between 2005 and 2007, Bloomberg New Energy Finance reported that "fundraising for companies in the battery transportation sector has dominated battery fundraising and continues to increase for companies developing Li-ion" (2007). Thus, such investment opportunities could have also incentivized an increase in new firm entry even though there was critical uncertainty regarding whether the same Li-ion battery used in consumer electronic products was a commercially viable solution for the electric vehicle market.

Furthermore, there was uncertainty in terms of what Li-ion battery technology architectural strategy automakers were going to capitalize on (i.e., laptop batteries or large-format purpose-built battery technology). Each battery strategy differed in the scale of Li-ion battery cells required for an electric vehicle (i.e., hundreds versus thousands of battery cells per vehicle). Thus, such technological uncertainty further exacerbated uncertainty in the expected future growth of demand for Li-ion battery technology in the electric vehicle market.

In addition, as patenting activity can be used as a crude indicator of innovation, Figure 3-1 a and b demonstrates the trends in granted patents on the battery cell-level and pack-level (by application market), respectively, during the period 2000 to 2018. Both graphs show a similar trend, across the same period, in terms of the efforts in (re-)configuring technological knowledge and capabilities to use Li-ion battery technology for electric vehicles. I acknowledge that both graphs represent trends in granted patents, which means that significant innovation efforts preceded those trends. However, from an entrepreneurial strategy perspective, the patenting activity during the observed period demonstrates the immense technological knowledge and capabilities that needed to be developed to resolve the technological uncertainty of using Li-ion battery technology for electric vehicles.

[Figure 3-1 a & b about here]

2.1.3 Uncertainty in the Reconfigured Market

Arguably, a considerable level of uncertainty regarding the expected growth of the electric vehicle market was reduced when Tesla Motors successfully commercialized its second electric vehicle – the Model S, in 2012. The Model S represented an astonishing inflection point in the automobile industry as it was the first electric vehicle to win the "Motor Trend Car of the Year" award, in 2013, by all measures (i.e., advancement in design, efficiency, engineering excellence, performance of intended function, safety, and value) used to determine the best car each year (Yeadon & Mackenzie, 2012). The architectural battery system for the Model S consisted of 7,104 Li-ion battery cells (more than the Tesla Roadster). Importantly, by that time, traditional automakers, such as Toyota and Daimler, had also adopted Tesla's battery strategy for their new models of electric vehicles. From an entrepreneurial strategy perspective, such application market dynamics generated a better sense of the expected size of the electric vehicle market for industry participants (e.g., incumbent battery manufacturers, battery start-ups, investors). Recognizing the success of the architectural battery system of the Model S, incumbent battery manufacturers realized that they needed to reconfigure their strategy for scaling battery production that had been originally implemented for the established consumer electronics market. For instance, by 2012, Amperex Technology Limited (ATL), which mass-produced Li-ion batteries for the consumer electronic market, had spun-off a new company called Contemporary Amperex Technology Limited (CATL) to scale production of Li-ion batteries for the electric vehicle market. As described by Herbert Diess (Former CEO of Volkswagen), such a strategic decision by the founder of CATL, Robin Zeng, was considered as an "exceptional transition" (2022). As another example, in 2014, Panasonic changed its strategy from a traditional battery supplier-relationship with Tesla to jointly build the Giga-Factory that would supply Tesla the battery cells for its electric vehicles. Such instances of strategic change further underscored the realization of the immense set of capabilities needed to scale battery production for the electric vehicle market.

Overall, this discussion suggests the importance of analyzing the interplay between the uncertainty associated with each application market and strategic decisions by entrepreneurial firms entering the industry. It took 15 years after the Li-ion battery was first commercialized in the consumer electronics market until its commercial viability was recognized in the electric vehicle market (i.e., which in retrospect started with the introduction of the Tesla Roadster in 2006). This contextualizes that the breadth of application markets for the Li-ion battery technology (i.e., conceptualized as a GPT) was not automatically predetermined and exogenous based on its technical features and viability in a single application market. As documented in Chapter 2, the applicability of the Li-ion battery across multiple application markets reflects the efforts of (re-)configuring industry knowledge and beliefs across multiple dimensions of uncertainty.

2.2 Relevance of context for entrepreneurial strategy

Several reasons make the Li-ion battery industry a unique context to investigate how the choice of entrepreneurial strategy is explained by the interplay between firm-level strategic decisions and the nature of uncertainty associated with application markets. First, prior theory on specialization-in-generality implies that during the mature stages of an industry (i.e., no uncertainty since the downstream buyers are easily identifiable), both incumbent and younger entrepreneurial firms faced the same set of strategic choices, i.e., specialize in developing upstream components, specialize in producing downstream products, or do both (Conti et al., 2019). However, throughout the observed period of the industry (1991—2023), battery start-ups entered as innovators of a battery cell component (i.e., modular innovation) or a battery cell architecture (i.e., architectural innovation). In other words, while most start-ups specialized in developing battery cell technologies, none of the start-ups entered as producers of downstream products (i.e., laptops or electric vehicles) primarily because no start-up had the capital nor the breadth of complementary assets to do so. Therefore, compared to incumbent battery manufacturers, start-ups were limited to a different set of choices for value creation and value capture, an observation that serves as a boundary condition in the theory of specialization-in-generality. Second, start-ups varied in their choice of targeted application markets. Although a battery sub-technology or a battery cell product could be developed to be applicable across broad or narrow application markets, start-ups made different choices regarding their targeted application market (i.e., consumer electronics, electric vehicles, or both), which varied in the level of uncertainty. A third important feature of the industry is that, during the observed period of the industry evolution, there was a significant demand shock with the introduction of an electric vehicle – i.e., the Tesla Roadster in 2006 – that in retrospect, generated a shift in the commercial value of Li-ion battery technology between the established consumer electronics market and the then-emerging electric vehicle market. Fourth, during the critical period of increasing uncertainty (2006—2012), start-ups entered with different Li-ion battery technology choices (i.e., battery component versus battery cell) with no consensus in the industry as to what architectural battery system (i.e., laptop batteries or large-format purpose-built batteries) would be the dominant design for the electric vehicle market, nor a winner-take-all strategy for either incumbent battery manufacturers or battery start-ups to scale production of Li-ion battery technology.

3. OBSERVED EMPIRICAL PUZZLE: SPECIALIZATION-IN-GENERALITY IN THE EVOLUTION OF THE LI-ION BATTERY INDUSTRY

After reviewing the high-level contextualization of uncertainty that battery start-ups faced, in this section, I look more deeply into the firm-level dynamics in terms of their strategic choices at entry: 1) choice of application market, and 2) choice of entrepreneurial strategy. To systematically compare how the choices of entrepreneurial entry strategies changed across the three distinct periods, I needed to document the strategic choices made by battery start-ups in each period.

3.1 Data sources & US-based battery start-ups

The data-generating process in collecting the quantitative data on US-based Li-ion battery start-ups started with a general search of firms in the battery manufacturing industry identified in the S&P Capital IQ database based on the Standard Industrial Classification (SIC) codes 3691 (storage batteries – rechargeable) and 3692 (primary batteries – non-rechargeable). Although the SIC code 3692 represented firms involved in manufacturing non-rechargeable batteries, it enabled me to tease out the diversifying entrants from start-up entrants. Additionally, I went through each company's "Business Description" – based on the S&P Capital IQ documentation – by keyword search (see Table A-1 in Appendix) to distinguish the firms developing Li-ion batteries from those involved in only developing incumbent rechargeable battery technologies (i.e., lead acid, NiCd, and NiMH). Next, I further identified and matched Li-ion battery start-ups that were listed as attendees in the International Battery Seminar (industry conference, est. 1983) during the period 2019—2022, as members in the NAATBatt International (not-for-profit trade association, est. 2007), as members in the New York Battery & Energy Storage Technology Consortium (est. 2010), and those that were listed in other databases, such as i3 Connect database (known for tracking global data on Clean Tech firms), Crunchbase, and Pitchbook.

In the dataset, start-ups were identified as new entrants if they had no existence prior to entering the industry, or they were spinouts that are entrepreneurial ventures of ex-employees of industry incumbents, which are considered as a subcategory of start-up entrants, and they were not an incumbent-backed firm (i.e., joint ventures, subsidiaries), which are considered as separate legal entities with formal ties (Kapoor & Furr, 2015). The final sample is the population of 151 new entrants that were founded in the US as innovators at the battery cell-level.

Figure 3-2 demonstrates the patterns of US-based start-up entry and exit throughout the evolution of the Li-ion battery industry. The green bars illustrate the number of yearly start-up entrants, whereas the red bars represent start-up exits (via acquisition or out of business), and the gray bars represent the yearly cumulative number of start-up entrants. It is important to note that during the observed period, the cumulative representation also includes start-ups that exited which totaled 42 exits, thereby limiting the survival bias in the analysis. Since this study focuses on the critical period 2006—2012, the list of US battery start-ups founded during this period consisted of 57 firms. In comparison, there were 26 battery start-ups founded in the first period (1991—2005) and 68 battery start-ups were founded in the third period (2013—2023).

[Figure 3-2 about here]

3.2 Observation 1: Choices of targeted application market

To document the choices of targeted application market for each start-up, I utilized the Internet Archive Wayback Machine (https://archive.org/web/) to browse each business's history in its official website since its founding year (or the year of first data availability), as illustrated in the Appendix Figure A-1. For start-ups that did not have website information during the early stage of founding, I utilized the Small Business Innovation Research (SBIR) and Small Business Technology Transfer

(STTR) programs website (https://www.sbir.gov/) to browse the approved federal grants for start-ups. The abstract of each relevant approved grant included information about what Li-ion battery technology the start-up was developing and the choice of targeted application markets (see Figure A-2 in Appendix). Start-up's whose choice of targeted application market included applications within the consumer electronics market and/or others (i.e., medical, military, excluding electric vehicles) were identified as start-ups that selected a *low-uncertainty* market environment. Alternatively, start-ups choosing targeted application markets that consisted of only electric vehicles were identified as start-ups that selected a *high-uncertainty* market environment. Lastly, start-ups that selected consumer electronics and/or others, as well as electric vehicles as their targeted application markets were identified as those that selected a *mixed-uncertainty* market environment.

Based on the choices of targeted application markets across the sample of battery start-ups, I identified 15 application markets for the Li-ion battery technology: 1) Consumer electronics, 2) Power tools and equipment, 3) Electric two-wheelers, 4) Unmanned aerial vehicles (UAV), 5) Medical, 6) Industrial, 7) Uninterruptible power supply (UPS), 8) Telecommunications, 9) Robots, 10) Military, 11) Marine, 12) Automotive, 13) Aerospace, 14) Grid energy storage systems, 15) Other specialty.

3.3 Observation 2: Choices of entrepreneurial strategy

As I map the battery start-ups to the entrepreneurial strategy framework (Gans, Scott, & Stern, 2018), the *value creation hypothesis* refers to the extent to which the start-up is challenging the status quo of the Li-ion battery technology architecture (at the cell-level) and its implication on the conventional battery cell manufacturing process. In addition, viewing the Li-ion battery cell technology through a technological system lens (Arthur, 2007, 2009) broadens the scope of understanding how start-ups engaged in the process of configuring their value creation and value capture strategies. These strategies apply not merely at the overall technological system product-level (i.e., an electric vehicle), but essentially incorporate innovations at the sub technology-level (i.e., developing battery components or battery cells). Figure 3-3 illustrates the basic principles of a Li-ion battery cell that is composed of sub-technologies combined in an architectural form (i.e., cylindrical) for a purpose (i.e., to provide electrical energy) across an array of application markets. A conventional Li-ion battery technology consists of a standard stack of sub-technologies (i.e., components): cathode, anode, electrolyte, and separator. In addition, Figure 3-4 illustrates the conventional manufacturing process for Li-ion battery cells, which consists of three key stages: electrode manufacturing, assembly, and formation. I focus on the entrepreneurial strategies by battery start-ups at the cell-level because most of the innovative activity (i.e., patenting) is around the battery cell components and the nano-scale intercalation process. Throughout the evolution of the industry, while 89 (59%) start-ups entered as battery component innovators, 62 (41%) start-ups entered as battery cell-architecture disruptors (i.e., manufacture battery cells and/or redefine the battery-cell architecture). On the other hand, the *value capture hypothesis* refers to the start-ups' orientation towards cooperating with or competing against the incumbent battery manufacturers.

[Figure 3-3 about here]

[Figure 3-4 about here]

Figure 3-5 illustrates the conceptualization of entrepreneurial strategies by battery start-ups in the value chain of manufacturing Li-ion battery cells for downstream application markets. The choice of *value chain strategy* represents start-ups that entered with a battery component and oriented to cooperate with incumbent battery manufacturers and/or application producers by fitting into (i.e., *Drop-in*) the existing value chain of manufacturing battery cells rather than upend it. Practitioners refer to such cell-component innovation as a "drop-in solution"; "[…] components that can drop into existing [battery] factories and the many [battery Giga-] factories being built around the world…" (Berdichevsky & Yushin, 2020, p.20). *Specializing-in-generality strategy* can be considered as a type of a value chain strategy in which the start-up develops their battery technology to drop-into existing battery production processes that requires minimal or no changes to the conventional manufacturing process and be targeted for multiple application markets. In contrast, the choice of a *disruptive strategy* is a more ambitious and competitive approach. It represents start-ups that choose to vertically-integrate by producing battery cells based on either the conventional or a redefined battery-cell architecture and oriented to compete against incumbent battery manufacturers.

[Figure 3-5 about here]

3.4 Central findings: Descriptive statistics for entrepreneurial strategies

Table 3-1 shows the descriptive statistics across the three distinct periods, in which battery start-ups varied in their choice of targeted application market (characterized by different levels of uncertainty) and entrepreneurial strategy at entry (see Figure 3-6 for graphical representation). It illustrates the relationship between firm-level heterogeneity, based on start-ups' choice of targeted application market and their choice of entrepreneurial strategy at entry.

In each period, the potential application markets differed in terms of size, scale of batteries required per product, and level of uncertainty. Given that the focus of this study is seeking explanations for the observed empirical puzzle in the period of Resurfacing Uncertainty, I begin by analyzing the strategic choices of battery start-ups during the critical period of *increasing uncertainty* (2006—2012). Then, to illustrate how uncertainty matters, I compared the strategic choices during the critical period of increasing uncertainty with those during the first (1991—2005) and third (2013—2023) periods, both of which experienced *decreasing uncertainty*. Thus, I document the alternative choices of entrepreneurial strategies within each period and show how those entry strategies changed over time.

[Table 3-1 about here]

[Figure 3-6 about here]

3.4.1 Entrepreneurial strategies under increasing uncertainty: 2006—2012

Columns 3 and 4 in Table 3-1 show the descriptive statistics for 57 battery start-ups founded between 2006 and 2012. During this period, 16% of start-ups entered with a specialization-in-generality strategy; that is, they selected both consumer electronics and electric vehicles as their targeted application markets with a value chain strategy. This finding can be interpreted as the breadth of demand for Li-ion batteries expanded to different application markets (including electric vehicle market), 16% of battery start-ups during this period selected a broad scope of application markets with a value chain strategy that was oriented to cooperate with incumbent battery manufacturers. In other words, they pursued an entrepreneurial strategy in a mixed-uncertainty environment.

However, specialization-in-generality strategy was not the dominant choice of entrepreneurial strategy because 84% of start-ups during the same period entered with alternative strategies. Notably, 35% of start-ups selected consumer electronics and/or others as their application market with a value chain strategy (versus 11% choosing consumer electronics with a disruptive strategy). On the other hand, 25% of start-ups selected a mixed application market with a disruptive strategy that was oriented to compete against incumbent battery manufacturers. Lastly, 9% of start-ups targeted only the electric vehicle market with a disruptive strategy (versus 5% choosing the EV market with a value chain strategy). This 9% could be considered to have a “moonshot” type of strategy, because not only was it oriented to compete against incumbent battery manufacturers, but it also marketed its technology for a high-uncertainty application. This was especially true during a time when consumer electronics was a low-uncertainty market and considerably larger than the electric vehicle market.

3.4.2 Entrepreneurial strategies under decreasing uncertainty: 1991—2005

Columns 1 and 2 in Table 3-1 show the descriptive statistics for 26 battery start-ups founded between 1991 and 2005. During this period, only one start-up entered with a specialization-in-generality strategy (4%); that is, only one firm (i.e., CAMX Power) selected both consumer electronics and electric vehicles as their targeted application market with a value chain strategy (versus 15% choosing both markets with a disruptive strategy). On the other hand, 42% of start-ups selected consumer electronics and/or others as their application market with a value chain strategy that was oriented to cooperate with incumbent battery manufacturers, while 35% of start-ups selected consumer electronics and/or others as their application market with a disruptive strategy that was oriented to compete against incumbent battery manufacturers. Again, this suggests that a specialization-in-generality strategy was not the dominant choice of entrepreneurial strategy during the early period of the Li-ion battery industry. Intuitively, most start-ups likely targeted the consumer electronic market because it was a proven and growing market for Li-ion battery technology during this period and there was no real market for Li-ion batteries in the electric vehicle market. Lastly, 4% of start-ups targeted only the electric vehicle market with a disruptive strategy (and none selected the EV market with a value chain strategy).

3.4.3 Entrepreneurial strategies under decreasing uncertainty: 2013—2023

Columns 5 and 6 in Table 3-1 show the descriptive statistics for 68 battery start-ups founded between 2013 and 2023. During this period, more start-ups (38%) chose mixed application markets with a value chain strategy, i.e., specializing-in-generality. This finding is consistent with prior theory on specialization-in-generality; that is, as the breadth of demand for Li-ion batteries further increased across multiple application markets, more start-ups selected a broad scope of application markets with a value chain strategy that was oriented to cooperate with incumbent battery manufacturers. In other words, more start-ups pursued a specialization-in-generality strategy in a mixed-uncertainty environment. Although more start-ups selected a specialization-in-generality strategy, it was still not the dominant choice of entrepreneurial entry strategy because 62% of start-ups during the same period pursued alternative strategies. Notably, 24% of start-ups selected mixed application markets with a disruptive strategy that was oriented to compete against incumbent battery manufacturers. In addition, even though the electric vehicle market seemed to be growing, 21% of start-ups still selected consumer electronics and/or others as their target application market with a value chain strategy (versus 7% choosing consumer electronics and/or others with a disruptive strategy).

Furthermore, 7% of start-ups targeted only the electric vehicle market with a value chain strategy (versus 3% choosing EVs with a disruptive strategy), which was an increase compared to prior periods. Although targeting only the electric vehicle market was a risky innovation bet, doing so with a value chain strategy was less risky than doing so with a disruptive strategy, given that a value chain strategy involves lower barriers to getting adopted within the value chain of manufacturing battery cells for electric vehicles.

4. POSSIBLE EXPLANATIONS

By triangulating the preceding historical account of the evolution of the Li-ion battery industry, firm-level quantitative and qualitative data, and prior studies seeking to explain the choice of entrepreneurial strategy when firms are faced with a broad scope of application markets, I generate the "lot" of five possible explanations – *specialization-in-generality, economies of scope, lower barriers to entry, overcoming liability of newness, and resurfacing uncertainty*. The process of generating the lot of possible explanations started with the theory of specialization-in-generality, since the specializing-in-generality strategy has been hypothesized as a viable strategy for entrepreneurial firms that face a broad scope of application markets and/or lack the capabilities to vertically-integrate and produce products in downstream markets. By observing that the specialization-in-generality theory has less explanatory power in this context, I turned to other theories in strategy research as possible explanations and evaluated each one to infer the best possible explanation for the observed empirical puzzle. The logic of such an abductive process is that if the explanation is our "best" possible explanation for the observed empirical puzzle in this context, then we should observe the pattern of choices by battery start-ups as predicted by the theory. If we do not observe start-ups acting accordingly, then it is either "not a likely" explanation or a "likely" explanation but not a "lovely" explanation (i.e., not a good fit for the observed empirical puzzle) (Goldfarb et al., 2022).

I now consider the following five possible explanations for the observed pattern of strategic choices for battery start-ups, during the period of Resurfacing of Uncertainty (2006—2012), that were inconsistent with the predictions of some prior theory in strategy research.

4.1 Specialization-in-generality

If prior theory of specialization-in-generality is the best possible explanation for the observed empirical puzzle; that is, if start-ups faced an increase in the breadth of application market scope, then most start-ups would be choosing to specialize-in-generality (i.e., valuing scope over scale) because it would allow them to sell their battery technology across multiple application markets, thus, yield higher expected returns (Conti et., 2019).

However, in this context, I observe only 16% of the start-ups choosing to specialize-in-generality while 84% of start-ups choosing alternative strategies. Notably, more start-ups were still choosing the consumer electronics market (35% of start-ups choosing consumer electronics with a value chain strategy and 25% of start-ups choosing both markets with a disruptive strategy). During the Resurfacing Uncertainty period, it was not obvious that choosing to specialize-in-generality would yield higher expected returns because the consumer electronics market demonstrated a steadily growing demand trajectory (as demonstrated in Figure 3-7) and there was low uncertainty in terms of the overall demand for Li-ion batteries in such a market. In contrast, there was considerable uncertainty in terms of the scale of Li-ion batteries required in electric vehicles as well as the expected size of such a market. In addition, the consumer electronics market was, at that time, significantly larger than the then-nascent market for electric vehicle batteries. Therefore, I conclude that this explanation has less explanatory power in this context.

[Figure 3-7 about here]

4.2 Economies of scope

If the theory of economies of scope is the best possible explanation for the observed empirical puzzle, then we would expect start-ups that were capable of scaling for market A would be capable of scaling for market B as an unproblematic process. Here, scaling capabilities refers to the start-ups' ability to raise more money to finance their operations for mass production and sell to applicable markets or their ability to seamlessly commercialize their technology across different application markets based on their experience in prior application markets.

However, in this context, if we consider the Technology Readiness Level (TRL) scale in Figure 3-8 (adapted from Frith, Lacey, & Ulissi, 2023), to go from a battery prototype stage of $10,000 to manufacturing Li-ion batteries for the electric market of

$10 billion is a 1,000,000-fold difference in scale. Thus, it is not reasonable to think that a start-up is indifferent to a million-fold challenge of scaling. It implies that a battery start-up could potentially manufacture battery cells for the consumer electronics market if they were able to reach a TRL 6, which requires an estimated capital investment of $500 million to $1 billion. However, to manufacture batteries for the electric vehicle market at scale would require further development stages (i.e., reaching TRL 8 – 9) and a significantly larger amount of capital investment that approximates between $1 billion and $10 billion.

[Figure 3-8 about here]

From an *entrepreneurial firm-level perspective*, to replicate prior best practices of battery production for the new electric vehicle market is difficult because the scale of Li-ion batteries required, level of risk involved, and capital investment needed for the electric vehicle market were fundamentally different from that for any application in the consumer electronics market.

Start-ups faced considerable *technical and financial* challenges as they tried to scale their technology for either or both potential application markets, i.e., consumer electronics, electric vehicles. In other words, although an engineered silicon anode (i.e., battery cell component) may possess a “general-purpose” feature, start-ups innovating such a battery technology were not able to commercialize across multiple application markets. For example, a successful growing start-up like Sila Nanotechnologies was founded in 2011 and selected to specialize-in-generality for its battery component (i.e., silicon anode). After 13 years of research and development in battery chemistry, more than 70,000 of material iterations, and raising about $938 million of funding (grants and venture capital), Sila's battery technology was first commercialized in a consumer electronic product – i.e., fitness wearable: Whoop 4.0 (Bellan, 2021). Yet, the start-up's battery technology has still not been commercialized in the electric vehicle market yet (note: Automaker Mercedes has been testing Sila's battery technology, which is expected to commercialize in the electric version of the automaker's G-Class SUV in 2025 (Randall, 2023)). There are other similar cases of battery start-ups, such as Amprius and Enovix that selected both consumer electronics and electric vehicle markets, yet, after more than a decade in the process of commercial development and raising millions of dollars of funding have not commercialized their battery technology in the electric vehicle market.

From a *technical perspective*, the development of battery technology is challenging and time consuming. To prove that a given battery technology was commercially viable, start-ups were required to go through long development cycles of material iterations and conduct time-intensive experiments to achieve the targeted performance indicators (i.e., life span, energy density, power, etc.) without harming the already demanded battery attributes (i.e., cost, safety) for a particular application. It took on average seven to 10 years to commercialize battery technology. In other words, even after a start-up demonstrated a workable lab-scale battery technology, the choice of a targeted application market presented the start-ups with a host of new challenges because each application market has different constraints in terms of the scale and complexity, such as duration of development cycles, technical performance requirements, and scale of batteries required in each application. It is important to note that using Li-ion batteries for electric vehicles at such a scale (i.e., 6,831 cells per vehicle) was a daunting engineering and manufacturing challenge. For example, battery start-ups, like A123 Systems had scalable battery technology for the power tools market but had to develop further scaling capabilities when they turned their attention to the electric vehicle market.

From a *financial perspective,* overlaying the venture capitalist (VC) model onto battery development was a problem, which was not obvious during the period of Resurfacing Uncertainty. While the VC model functions on a particular timeline in which investors expect a return on investment, battery development is a multi-stage, multi-year process, which fundamentally did not fit with the VC model. Thus, the nature of the technological challenges associated with developing battery technology was not well-understood by the investors.

I conclude that scaling battery technology is obviously harder than the theory would predict, therefore, the possible explanation of economies of scope is inconsistent with what I observe in this context.

4.3 Lower barriers to entry

If lower barriers to entry is our best possible explanation; that is, if an emerging market lower barriers to entry and creates new opportunities, then more startups would choose to enter the new market. Since the early period of a new market is characterized by high uncertainty, battery start-ups selecting the new electric vehicle market could face lower barriers than that in later periods for their battery technology to be adopted in the value chain of manufacturing battery cells for electric vehicles.

However, in this context, I observe entry by 57 start-ups during the period of Resurfacing Uncertainty (as illustrated in Figure 3-6), but not into the new electric vehicle market because the idea of it is a new market would lower barriers to entry does not explain the choice of uncertainty among entering firms. There were more battery start-ups (35%) that still selected to target the well-established consumer electronics market. This suggests that even though the electric vehicle was considered as a new application market, it was still not regarded as the most desirable market choice at entry. Therefore, I conclude that the explanation of lower barriers to entry is weakly supported in this context.

4.4 Overcoming liability of newness

If we consider that overcoming liability of newness is the best possible explanation; that is, if institutional pressure for the development of battery technology for the electric vehicle market makes it easier for start-ups to raise money if they purse the electric market, then start-ups choosing the electric vehicle market with either a value chain or disruptive strategy would have been able to raise more money. Presumably between 1991 and 2005, there would be a liability of newness in terms of using Li-ion batteries for consumer electric vehicles. In fact, institutional incentives (i.e., governmental grants & subsidies, VC funding, change in policy) for innovating battery technology in the electric vehicle market has been an ongoing phenomenon since the early 1990s. By 2006, the commercialization of Li-ion batteries in a consumer electric vehicle should have ended the liability of newness and we would expect to observe a rational allocation of resources to the new application market.

However, Table 3-2 shows that during the period of Resurfacing Uncertainty, start-ups that were raising more money – based on a three-year average of investments (i.e., millions of dollars of early-stage funding: VC & grants) since founding – were those choosing both application markets with a disruptive strategy (see Figure 3-9 for graphical representation). This implies that start-ups were still able to acquire more resources by developing battery technology for the consumer electronics market. Yet, this explanation would have predicted that start-ups choosing the electric vehicle market should be raising more money. Therefore, I conclude that this explanation is weakly supported in this context.

[Table 3-2 about here]

[Figure 3-9 about here]

4.5 Resurfacing uncertainty

The Resurfacing Uncertainty explanation would suggest that facing multiple dimensions of uncertainty, strategic bets placed by start-ups entering this industry reflected their preferences and beliefs about the nature of those uncertainties (see conceptual framework in Figure 3-10).

The increasing level of uncertainty based on the interdependencies of multiple dimensions – i.e., application market, technological, business model and value chain, and institutional – generated uncertainty profiles that differ for each application market. The strategic bets reflect the start-ups' preferences and beliefs of those uncertainties that consider the expected returns, challenges of scaling, and timing of entry. So, even if the expected return is positive to choose a specialization-in-generality strategy, it is hard to get funding to do it. Scaling is so challenging that vertical-integration (i.e., producing batteries and downstream products) is not really a choice for a start-up, and choosing to scale production of Li-ion battery technology is different between consumer electronics and electric vehicles. As I also argue that the timing of entry fundamentally influenced the success and failure of battery start-ups.

[Figure 3-10 about here]

Start-ups choosing either a value chain or a disruptive strategy were placing a different strategic bet that depended on which uncertainty-market environment they selected to enter. Importantly, choosing a disruptive strategy in a low-uncertainty market environment was very different from a disruptive strategy in a mixed- or high-uncertainty market environment because they were considered as strategic bets with different risk profiles. Start-ups that entered during the second period faced a low-uncertainty consumer electronics market (i.e., steady growth market) and high-uncertainty electric vehicle market (i.e., emerging market).

In terms of technological uncertainty, historical record indicates that it was not obvious which architectural battery system automakers were going to capitalize on (i.e., laptop or large-format purpose-built Li-ion battery technology). In fact, up until 2012, Tesla's battery strategy of using thousands of laptop batteries was not viewed as a standard for the electric vehicle market. Before that time, Toyota was the market leader in selling hybrid electric vehicles (HEVs) that used large-format purpose-built NiMH batteries (i.e., incumbent battery technology) supplied by incumbent battery manufacturers, i.e., Sanyo and Panasonic who had a combined share over 85% of NiMH HEV battery market (Bloomberg New Energy Finance, Dec 11, 2007). Those same incumbent battery manufacturers (first Sanyo and then Panasonic) eventually agreed to supply Tesla with laptop Li-ion batteries for their first electric vehicles of Tesla Roadsters. Each architectural battery system had different implications for firms in choosing their strategy to scale battery production. Therefore, in terms of business model and value chain uncertainty, it was not clear what would be the winner-take-all scaling strategy (i.e., supply, ally, or integrate) for incumbent battery manufacturers to meet the expected demand across multiple application markets.

Furthermore, in terms of application market (size and scale) uncertainty, while the electric vehicle represented an emerging application market for battery start-ups, it was difficult for industry experts to predict what would be the optimal scale of batteries required for each vehicle and when the adoption of Li-ion batteries in such a market would take off (i.e., commence a "hockey-stick" growth). For instance, Figure 3-11 shows that even industry expert forecasters (as reported in multi-year forecasts from Bloomberg New Energy Finance reports) had predicted that the electric vehicle market would take off sooner, which resulted in overestimating the growth trajectory of the market for several years. It also demonstrates that industry experts were updating their industry knowledge about the growth of the electric vehicle market, such that predictions between 2013 and 2014 were closer to the actual sales of electric vehicles.

[Figure 3-11 about here]

This suggests that while the growth of the electric vehicle market was more obvious for battery start-ups founded during the third period, this was not the case for battery start-ups founded in the second period (2006—2012). In fact, during the second period, the market for consumer electronics was clearly growing and significantly larger than the electric vehicle market. Therefore, while prior studies on specialization-in-generality have some explanatory power as to why some start-ups selected a mixed application market with a value chain strategy, they do not explain why other start-ups selected a mixed application market with a disruptive strategy, which is considered very risky given the limited capabilities of battery start-ups. In addition, the reason other start-ups were still choosing to develop Li-ion battery technology only for the well-established consumer electronics markets is left unexplained when following the specialization-in-generality theory.

From an entrepreneurial strategy perspective, it could be the case that, during the first period of decreasing uncertainty and stable growth of demand for Li-ion batteries in the consumer electronics market, barriers to entry increased and made it difficult for battery start-ups to enter with more of a disruptive strategy because the industry was dominated by highly specialized and well-resourced incumbent battery manufacturers, such as Sanyo, Sony, Matsushita, A&T, GS Melcotec, NEC Moli, and Hitachi. In addition, choosing a disruptive strategy for a Li-ion battery technology would have higher barriers to getting adopted in a highly integrated value chain for manufacturing battery cells. But the increasing level of uncertainty triggered by the successful commercialization of a consumer electric vehicle (i.e., industry demand shock of the Tesla Roadster) spurred start-ups to enter with different strategic bets; it also triggered investors to support those bets. The fact that both public (i.e., governmental agencies) and private (i.e., angel investors, venture capitalists and corporations) investors funded start-ups choosing a disruptive strategy (i.e., big innovation bet), further suggests that incumbent battery manufacturers did not have the advantage of a winner-take-all strategy for the electric vehicle market as they previously had in the consumer electronics market.

Historical records revealed that start-ups in the Li-ion battery industry faced different levels of uncertainty depending on their choice of targeted application market. For instance, start-ups that targeted the electric vehicle market (i.e., high-uncertainty market), as opposed to the consumer electronics (i.e., low-uncertainty market), had to develop further capabilities (i.e., raise funding, conduct longer development cycles, attract partnerships) that were not obvious when the electric vehicle market itself was in its developmental stages. Thus, the level of uncertainty associated with multiple dimensions – technological, application market, business model and value chain, and institutional – became strategically critical for firms during the period of increasing uncertainty.

Therefore, I conclude that the Resurfacing Uncertainty explanation is obviously context specific, which may not generalize. However, this explanation is the best explanation I've arrived at in an industry that is still in its growth stage and is expected to grow five to 10 times larger in the next decade. The strategic choices that start-ups were making are not explained by any single parsimonious theory, so what we have is a complex landscape on which start-ups are acting.

5. GENERALIZABILITY

The single-industry nature of this study may limit generalizability. However, the analysis reveals useful insights to be explored across different industry contexts that might experience application-related market demand shocks. For instance, in the 3D-printing industry, the conventional wisdom is that firms use 3D-printing technology for prototyping and not manufacturing products. However, more recently, a start-up car company, called Czinger, has introduced a supercar that was made using sophisticated

3D-printing technology. According to industry analysts, if such 3D-printing technology is proven successful, “it will be an earthquake for the [3D-printing] industry” (Warren, 2022). In other words, if conventional assumptions about potential uses for 3D-printing were proven wrong, then that could dramatically change the scale of the market for 3D-printing, to include not only prototyping but also production. Incumbents may not be able to meet the demand of the whole market in the same way as they used to with the established prototyping market; therefore, it could trigger increasing uncertainty with regards to the future scale of the emerging market, and start-ups might enter with different uncertainty profiles and place different strategic bets.

6. IMPLICATIONS: ENTREPRENEURIAL STRATEGY FOR GPTs UNDER UNCERTAINTY

The deep dive analysis of this study aligns with the perspective of recent studies on entrepreneurial strategy that suggests “rather than emphasizing an environmental approach to entrepreneurial strategy in which conditions (e.g., market, technology, industry) are predetermined and exogenous to the entrepreneur, the choice of entrepreneurial strategy is in large part a choice of the environment itself. […] For example, if a start-up chooses to engage an initial customer segment that has been neglected by established players (at the opportunity cost of a strategy that focuses on mainstream consumers from the start), the start-up could be assessed ex post to be constrained by the niche sector they are located in rather than acknowledging the endogeneity of that choice from the outset” (Gans et al., 2019, p.738-739). However, this study sheds light on how uncertainty can be a choice that the start-up makes and how this strategic choice presents the start-up with different layers of sequential challenges to scale their GPT.

Recent studies on the micro-foundations of GPTs have examined firm strategy in the laser industry. Lasers have been commercialized across "biomedical/medical (e.g., medical imaging, dermatology), information processing (e.g., scanning, optical disk reading), telecommunications (e.g., data transmission, pulse generation), military (e.g., target designation), and industrial (e.g., cutting, welding, marking) applications" (Conti et al., 2019, p.133). Conti et al. (2019) have hypothesized that when the breadth of demand across application markets for an enabling technology expands over time, it fosters the emergence of firms pursuing a "specialization-in-generality" strategy in intermediate markets; that is, investing in developing general upstream resources and trading them in downstream markets. Such a strategy has been examined in different industry contexts in strategy research (Conti et al., 2019; Wormald et al., 2021).

Specifically, in the laser industry setting, Conti et al. (2019) shows that, after a regulatory shock, firms were more likely to choose a specialization-in-generality strategy when they lacked downstream assets and/or faced a broader demand in downstream markets. In such a tightly integrated value chain and mature industry setting with no uncertainty, entrepreneurial firms are more likely to specialize in producing sub-technologies (i.e., laser components) rather than producing specialized products (i.e., laser products). Such work has encouraged a more dynamic view in the breadth of application markets for a GPT when examining firm strategies. Thus, it has generated useful insights regarding the market conditions (i.e., supply- and demand-side) for when and which firms are likely to pursue a specialization-in-generality strategy. In another context of patented inventions using survey-based data, Gambardella et al. (2021) formally extend Teece's (1986) seminal profiting from innovation (PFI) framework for innovators to better navigate external environment challenges in creating and capturing value for their enabling technology. The study finds that neither vertical-integration nor contracting are straightforward commercialization strategies for GPTs when compared with similar strategies for discrete technological innovations.

However, in discounting the nature of uncertainty (i.e., high/low or no uncertainty), studies have identified the specialization-in-generality strategy as viable in a mature industry setting (like in the laser industry), where firms are more likely able to identify unique downstream buyers based on the technology's technical characteristics. It assumes that entrepreneurial firms can scale their technology across multiple application markets by choosing the relevant technology for each market. Studies have also assumed that the development process of a technology's generality across application markets is an unproblematic process (i.e., assumed given). Thus, firms are making such strategic choices as if the attributes (i.e., actual size, expected growth rate) of potential application markets are known. Therefore, it limits our understanding of how entrepreneurial firms make strategic choices when application markets are characterized by different sizes and levels of uncertainty in terms of future market growth. In other words, how do entrepreneurial firms choose their strategy when the scale and scope of potential application markets for their technology is yet to be determined? Historical records have shown that the commercial value and potential applicability of the Li-ion battery technology only developed over time. Given the nature of uncertainty, it was not obvious for battery start-ups which strategic choices would yield the higher expected return. Thus, I find that uncertainty was fundamental for start-ups in choosing their entrepreneurial strategy as they possessed partial knowledge about the development of potential application markets for their battery technology. For instance, there was considerable uncertainty in terms of which Li-ion battery technology architecture would be the winning technology for use in electric vehicles, as well as uncertainty about the future size of such an application market.

The analysis of this study revealed a variety of questions that I present as conjectures to be explored in future research.

6.1 Conjectures

As documented in this study, uncertainty is not merely a predetermined or exogenous feature of the underlying context of technology, market, or industry (Gans et al., 2019), but also a choice that the entrepreneurial firm makes when selecting its strategic position.

C1: *Entrepreneurial firms can attract more resources by choosing a high-uncertainty market environment.*

Technology generality and its commercial value across multiple application markets only develops over time (Teece, 2018; Kapoor & Teece, 2021), for which reason, entrepreneurial firms lack complete information and clarity when choosing their scope of targeted application markets (i.e., narrow versus broad). This lack of information has implications for choosing their value creation and capture strategies. From a theoretical perspective, the specialization-in-generality framework would predict that an entrepreneurial firm would likely choose a value chain strategy when faced by demand across a broad scope of application markets (Conti et al., 2019). Thus, when uncertainty is low or negligible and technology's generality is predetermined by technical characteristics, entrepreneurial firms would more likely choose to specialize-in-generality because it would expand their choice set of downstream buyers and increase the likelihood of earning higher returns. However, what are the implications for choosing an entrepreneurial strategy when technology generality and its commercial value is not predetermined but rather a moving target across different application markets?

Based on start-ups in the Li-ion battery industry, selecting into different uncertainty environments positioned firms on different paths that necessitated developing different sets of capabilities (i.e., raising funds, creating partnerships) to support the different choices of entrepreneurial strategy (i.e., strategic bets). Thus, start-ups that selected consumer electronics and/or others as their targeted application market would likely be picking lower uncertainty signals, thereby gaining less leverage (i.e., funding, partnerships) to support a disruptive strategy. Consequently, those start-ups are more likely to choose a value chain strategy (versus a disruptive strategy). On the other hand, start-ups that selected both electric vehicles and consumer electronics and/or others or solely electric vehicles as their targeted application markets would likely be picking mixed- or high-uncertainty signals, respectively, thereby would attract more leverage (i.e., funding, partnerships) to support a bigger innovation bet, such as a disruptive strategy.

Thus, failing to account for the nature of uncertainty may put the entrepreneurial firm at greater risk. For instance, if the entrepreneurial firm assumes that scaling battery technology for camcorders is the same as scaling battery technology for electric vehicles, there is a higher possibility of failure. Overall, by distinguishing the nature of uncertainty associated with each strategic choice of application market, strategy scholars as well as practitioners can gain a deeper understanding when examining the potential risk of start-ups' choice of entrepreneurial strategy for their GPT.

C2: *Facing multiple application markets characterized by different levels of uncertainty, entrepreneurial firms may yield more favorable outcomes when choosing an alternative strategy than specialization-in-generality.*

The process by which an emerging technology transforms into a GPT that gets commercialized across multiple application markets is complex process and context specific. Yet, "knowing what worked in context A may be useful in thinking about what might work in context B" (Goldfarb & Kirsch, 2020). The studies on micro-foundations of GPTs (Teece, 2018; Conti et al., 2019; Gambardella et al., 2021; Wormald et al., 2021; Shermon & Moeen, 2022) have leveraged different contexts and generated useful insights regarding the antecedents (i.e., environment conditions, firm heterogeneity) for choosing firm strategy. To the best of my knowledge, no study has examined the effects of choosing an entrepreneurial strategy for a GPT on firm performance. Indicators of firm performance can include survival, funding raised, number of partnerships, type of partnerships, or number of application markets in which the technology was commercialized. Which choice of entrepreneurial strategy would increase the likelihood of firm success during periods of increasing uncertainty?

Thus, based on the analysis of start-ups in the Li-ion battery industry, entrepreneurial firms that selected consumer electronics and/or others as their targeted application markets (i.e., low-uncertainty market) and followed a value chain strategy would likely experience lower growth rate, lower risk of failure, less variability in stock price, more predictable returns – i.e., lower variance in performance outcomes.

On the other hand, entrepreneurial firms that chose only electric vehicles as their targeted application markets (i.e., high-uncertainty market) and followed an ambitious disruptive strategy (i.e., “moonshot” strategy) would be predicted to experience higher potential growth rate, higher risk of failure, higher variability in stock price, more volatile returns – i.e., higher variance in performance outcomes. Lastly, one could observe different dynamics for entrepreneurial firms that chose consumer electronics and/or others as well as electric vehicles as their targeted application markets (i.e., mixed-uncertainty market) and followed either a value chain strategy or disruptive strategy. In such cases, entrepreneurial firms that opted for a value chain strategy (i.e., specialize-in-generality) would be predicted to experience higher returns (Conti et al., 2019) and lower risk of failure – i.e., lower variance in performance outcomes – since they are more likely aiming to fit-into the value chain and cooperate with incumbent and/or start-up firms rather than competing against them. In contrast, entrepreneurial firms that opted for a disruptive strategy would be predicted to experience lower returns (at first) but higher returns later (if proven right) as well as higher risk of failure – i.e., higher variance in performance outcomes since they are more likely oriented to compete against incumbent and start-up firms.

C3: *Prior experience in scaling GPTs is not easily transferable.*

Some studies on micro-foundations of GPTs (Teece, 2018; Conti et al., 2019; Gambardella et al., 2021; Wormald et al., 2021; Shermon & Moeen, 2022) have led us to understand that the commercialization of a GPT in multiple application markets presents entrepreneurial firms with an opportunity, as it expands their choice of application markets to target. Thus, choosing to specialize-in-generality (i.e., choosing mixed-uncertainty and a value chain strategy in the context of the Li-ion battery industry) might seem to be the viable strategy because touting “TAM” (Total Addressable Market) often means that the firm is going after a larger market share. But what if choosing a broad scope of targeted application markets with either strategy (more so with a disruptive strategy) is a death knell for start-ups and sets them on an accelerated path to failure? In the Li-ion battery industry context, there were dozens of cases of start-up failure (as evidence) due to how they conceived the nature of uncertainty associated with each targeted application market and how they believed they were going to scale their technology for each application market.

A classic example of a US battery start-up failure is A123 Systems, which started by targeting the steady growing consumer electronics market and then expanded their scope of targeted application markets to electric vehicles (i.e., mixed-uncertainty) with a disruptive strategy. One explanation for their failure could be that they generated an ambitious assumption that the electric vehicle market would take off within a short duration, but it did not, and so the timing of their strategy was off (i.e., demand-side explanation for failure). Another explanation could be in their understanding of capabilities needed for scaling to supply a broad scope of application markets (i.e., supply-side explanation for failure). They might have believed that scaling capabilities in production of batteries for the power tools market (i.e., their initial commercialization market) are similar to the capabilities required for scaling batteries in the electric vehicle market. Even more recently, the co-founder of battery start-up Sila Nanotechnologies has implied that successfully commercializing battery technology in the consumer electronics market enables start-ups sufficient learning and complementary assets to leap into scaling and commercializing their technology for the electric vehicle market: “I’m not announcing that we’re in a car [electric vehicle] today, but I’m basically announcing that we’re in a car because if our technology can deploy in a consumer device, it can just as easily deploy in a car” (Berdichevsky, 2021). Yet, evidence of start-ups that have failed, A123 Systems and Sakti3 Inc., among others, suggests that the *challenges of scaling* are highly significant. Having market experience in small applications markets (i.e., consumer electronics) is different from having market experience producing batteries for larger application markets (i.e., electric vehicles). Overall, scaling is a set of sequential challenges. It is not as simple as “Can a start-up scale?” Each milestone in scale is a new challenge in the Li-ion battery industry.

7. CONCLUSION

Uncertainty is an inherent part of choosing an entrepreneurial strategy especially when the potential value of an application market is changing, and market dynamics are unstable.

Based on the analysis of this study, I suggest that the observed changing patterns of entrepreneurial strategic choices were triggered by the changing level of uncertainty associated with each potential application market start-ups selected into. I utilized multiple sources to extract data at the industry-, market-, technology-, and firm-level to understand the uncertainty start-ups faced at the time of their initial business planning that fundamentally influenced their choice of entrepreneurial strategy for their technology. I documented the critical industry events and patterns of start-up strategies across three distinct periods (i.e., 1991—2005, 2006—2012, and 2013—2023) in the evolution of the Li-ion battery industry. The purpose of examining such industry-, market-, technology-, and firm-level dynamics is to further identify potential mechanisms as possible explanations to the observed empirical puzzle, thus, aiding my research method approach of abductive inference to the best possible explanation. While the findings may not be fully generalizable as they are context specific, nevertheless, the Li-ion battery industry represents an important industry as it is currently in a growth stage and arguably going to be a significant contributor to the world's economy. Therefore, in this study, I aim to provide a richer understanding of start-ups choosing their entrepreneurial strategy for their battery technology as the commercial value across application markets changed.

From a theoretical perspective, this study contributes to strategy research on entrepreneurial strategies for GPTs under a dynamic nature of uncertainty (Furr & Eisenhardt, 2021). First, I contribute to the research stream showing how the strategic choices of entrepreneurial firms changed over the evolution of the industry context as the "general-purpose" feature of the focal technology developed over time. Some recent studies in strategy research have identified specializing-in-generality strategy as a viable choice for younger entrepreneurial firms that lack assets in downstream markets and/or face a broad market scope of demand for their technology (Conti et al., 2019, Wormald et al., 2021). Such studies have examined firm strategies in either the early stages of an industry (i.e., high uncertainty at emergence followed by decreasing uncertainty) or in mature stages of an industry (i.e., significant uncertainty has been reduced) in which the general-purpose feature of the technology is predetermined by its technical characteristics, and firms are more likely to identify potential buyers in downstream application markets. I instead broaden the lens by analyzing the choices of entrepreneurial strategies across three distinct periods in the evolution of the Li-ion battery industry from its first commercialization in 1991 to present (2023), because in each period, potential application markets differed in terms of size, scale of batteries required per product, and level of uncertainty. This feature enabled me to analyze the specialization-in-generality strategy under a dynamic nature of uncertainty (i.e., *ebb and flow*: decreasing then increasing then decreasing).

Second, prior research on specialization-in-generality implies that both incumbent and younger entrepreneurial firms (i.e., start-ups) are faced with the same set of strategic choices, i.e., specialize in developing upstream components, specialize in producing downstream products, or do both. By showing the firm-level heterogeneity across time and categorization of the start-ups' choice of technology within a technological system, I was able to further demonstrate that start-ups could choose to specialize-in-generality by entering with sub-technological components for the same technology (i.e., Li-ion battery). This is an observation that seemed consistent with prior studies in terms of how the evolving applicability of a GPT can spawn complementary innovations that start-ups could choose to specialize in and target multiple application markets, i.e., division of innovative specialization (Bresnahan & Gambardella, 1998). In addition, consistent with prior theory, I show that, even though the type of technological innovation is applicable across multiple application markets that only develop over time, the start-up's choice for the breadth of targeted application markets for its technology is not primarily driven by its technological characteristics but rather as a strategic choice. Furthermore, in this industry context, none of the start-ups had capabilities in producing downstream products. I explored this boundary condition by considering the uncertainty entrepreneurial firms faced when choosing their strategy for their technological innovation. While a specialization-in-generality strategy was observed to be pursued by entrepreneurial firms (i.e., start-ups), its prevalence as a choice of strategy changed over time. Thus, having established the findings in the context of the Li-ion battery industry, I contribute to the literature of entrepreneurial strategy for GPTs by highlighting that choosing a particular application market scope to target is not simply based on the choice of the applicable technology, but it is a *compounded choice*. Each application market is characterized by its size, challenges to scale, and level of uncertainty. To potentially commercialize a technology in a narrow or broad application market scope will require start-ups to develop different sets of capabilities (i.e., raise funding, generate strategic partnerships). Therefore, strategy scholars, considering the specialization-in-generality model to study firm strategy, need to consider the context carefully because new application markets present different challenges to innovators of GPTs, in which some strategic options (i.e., vertical-integration) may not be available for start-ups.

Lastly, this study contributes to research on entrepreneurial strategy and uncertainty (Gans et al., 2019; Rindova & Courtney, 2020; Furr & Eisenhardt, 2021). I demonstrate that although uncertainty of the environment is not controlled by entrepreneurial firms, they do control the choice of their preference of uncertainty based on their choice of application market. By explicitly demonstrating the development process of the general-purpose feature of the Li-ion battery technology with start-ups' choice of application market, I was able to identify the environmental and firm factors that shaped start-ups' choice of entrepreneurial strategy. Start-ups that entered the Li-ion battery industry in hopes of commercializing their technology faced a dynamic nature of uncertainty based on their time of entry and the application market they selected to target. In other words, when entrepreneurial firms faced application markets with different levels of uncertainty, the uncertainty becomes strategically relevant and a compounded choice as the applicability of the technology across potential application markets, such as the electric vehicle, was not clear.

As this study was conducted using a single-industry context, the findings should be generalized with caution. I observed that for the same technological innovation the dominant strategic choice to specialize-in-generality may change among entrepreneurial firms over time. While such a strategy may seem like a viable choice for entrepreneurial firms during the mature stages of an industry (Conti et al., 2019), it may not be the most feasible choice during the growth stage of an industry, as there is considerable uncertainty in the future development of potential application markets. Thus, it would be useful for future research to further explore our findings in different industries. In addition, future research may also examine what, how, and when environment changes can cause entrepreneurial firms to pivot towards or away from choosing a specialization-in-generality strategy.

Despite the limitations, this study provides some practical implications for technology entrepreneurs who are faced with a dynamic nature of uncertainty in terms of competing technology alternatives, developing breadth of applicable markets over time, and no "winner-take-all" strategy environment. While a specialization-in-generality strategy may seem like a viable choice for a technology entrepreneur because it expands their choice set of application markets to target, each choice of application market is associated with different levels and dimensions of uncertainty. Thus, technology entrepreneurs should assess the different dimensions of uncertainty associated with each choice of application market because choosing an alternative strategy, than specializing-in-generality, may yield more favorable outcomes on the pathway to commercialization.

The second study of this dissertation underscores the importance of distinguishing the different levels and dimensions of uncertainty associated with each potential application market as critical antecedents in shaping the choice of entrepreneurial strategy.

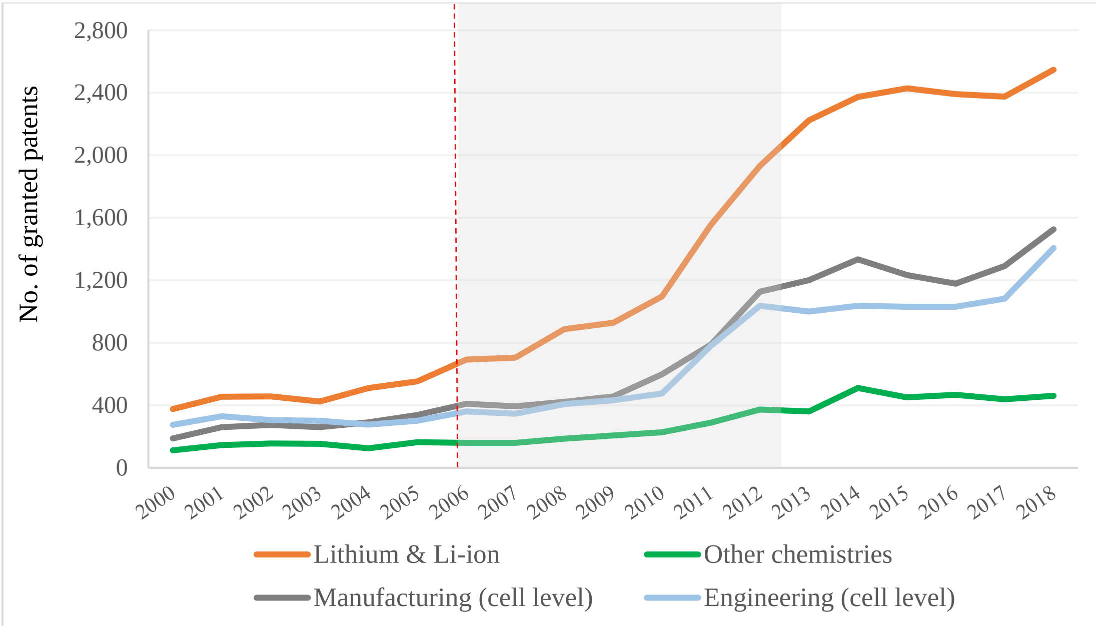

Figure 3-1a Patenting activity: Number of international patent families related to battery cells (2000—2018). *Source:* European Patent Office (EPO) reported in Gregori et al. (2020).

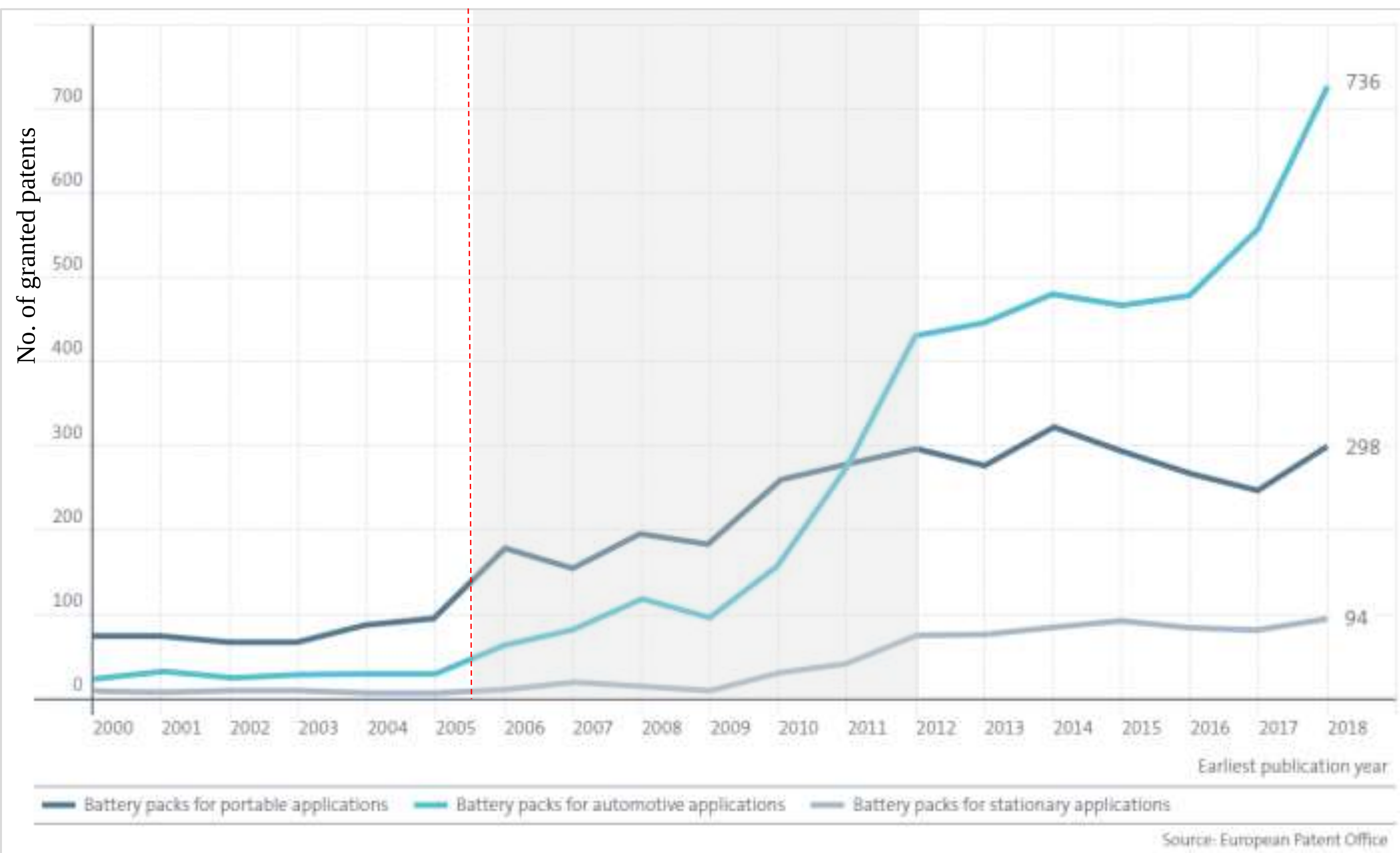

Figure 3-1b Patenting activity: Number of international patent families related to battery packs for different application markets (2000—2018). *Source:* European Patent Office (EPO) reported in Gregori et al. (2020).

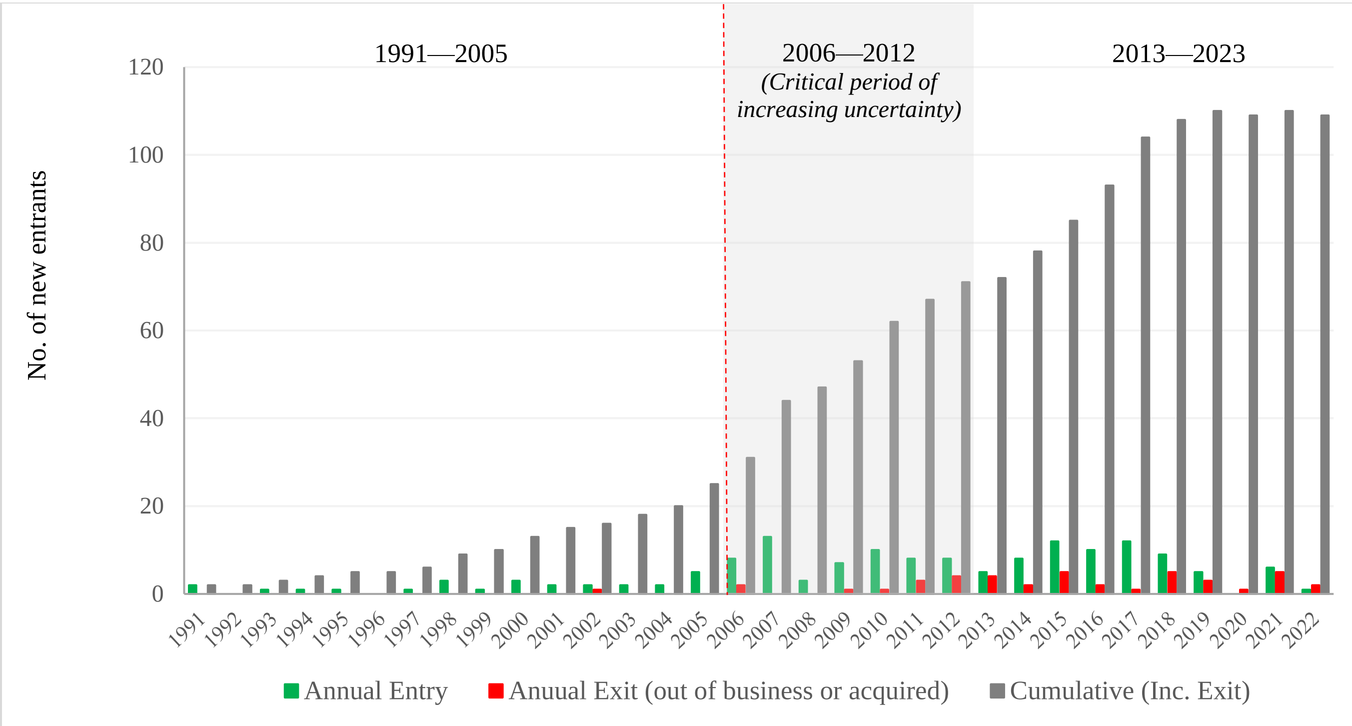

Figure 3-2 US-based start-up entry and exit in the Li-ion battery industry through a Market transformation lens (1991—2022).

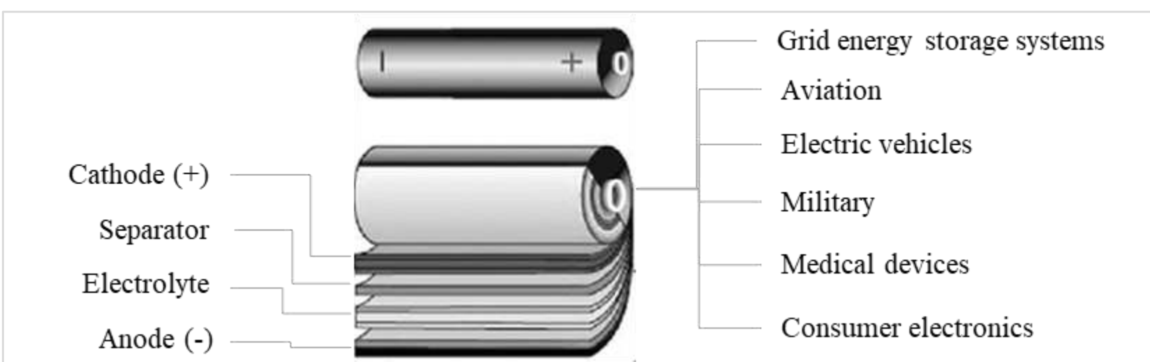

Figure 3-3 Cylindrical Li-ion battery cell architecture through a technological system lens.

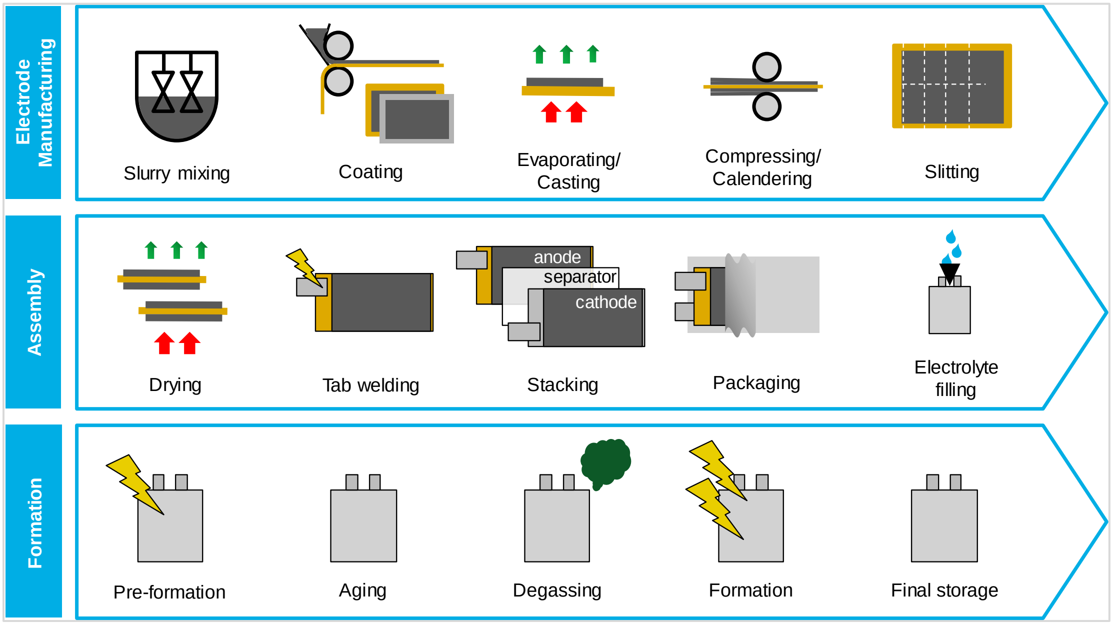

Figure 3-4 Conventional manufacturing process for Li-ion battery cells consists of three distinct steps: (1) electrode manufacturing, (2) component assembly & (3) formation. *Source:* Stoikou & Frith (2019).

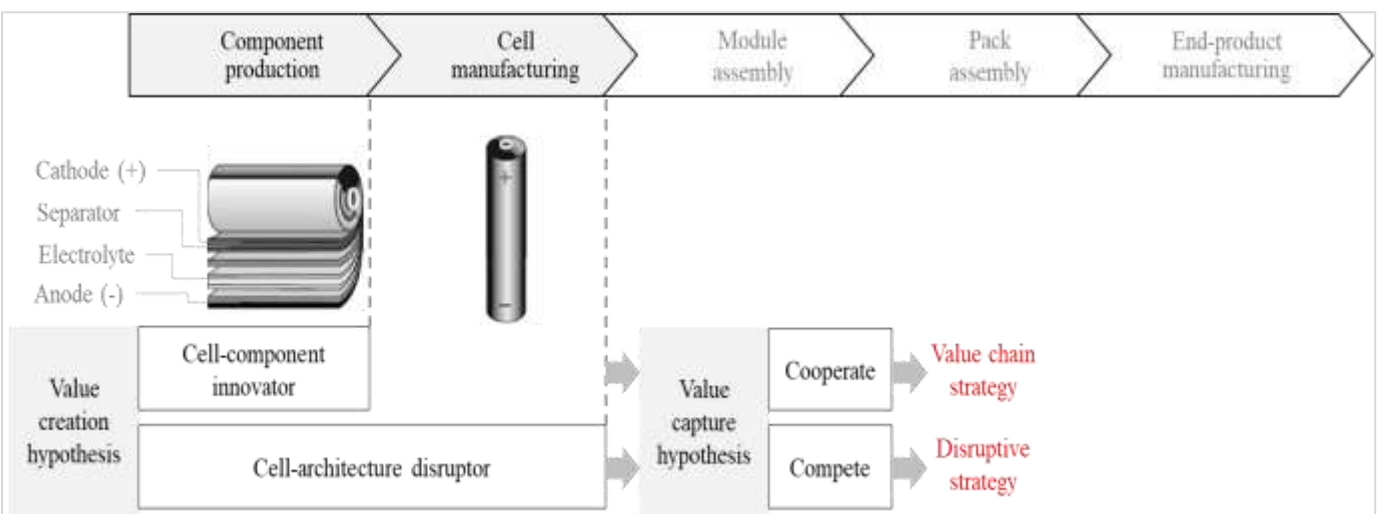

Figure 3-5 Mapping the strategies of US-based start-ups in the value chain of manufacturing Li-ion battery cells for downstream application markets to the entrepreneurial strategy framework.

Table 3-1 Summary statistics for the choices of entrepreneurial strategy at entry via value chain or disruptive in each period across the evolution of the Li-ion battery industry.

	Choice of entrepreneurial strategy					
	1st period 1991—2005		2nd period 2006—2012		3rd period 2013—2022	
	(1)	(2)	(3)	(4)	(5)	(6)
Choice of application market	Value Chain	Disruptive	Value Chain	Disruptive	Value Chain	Disruptive
Both *Mixed uncertainty*	1 4%	4 15%	9 16%	14 25%	26 38%	16 24%
Electric Vehicle *High uncertainty*	-	1 4%	3 5%	5 9%	5 7%	2 3%
Consumer electronics *Low uncertainty*	11 42%	9 35%	20 35%	6 11%	14 21%	5 7%
Total no. of start-ups	26		57		68	

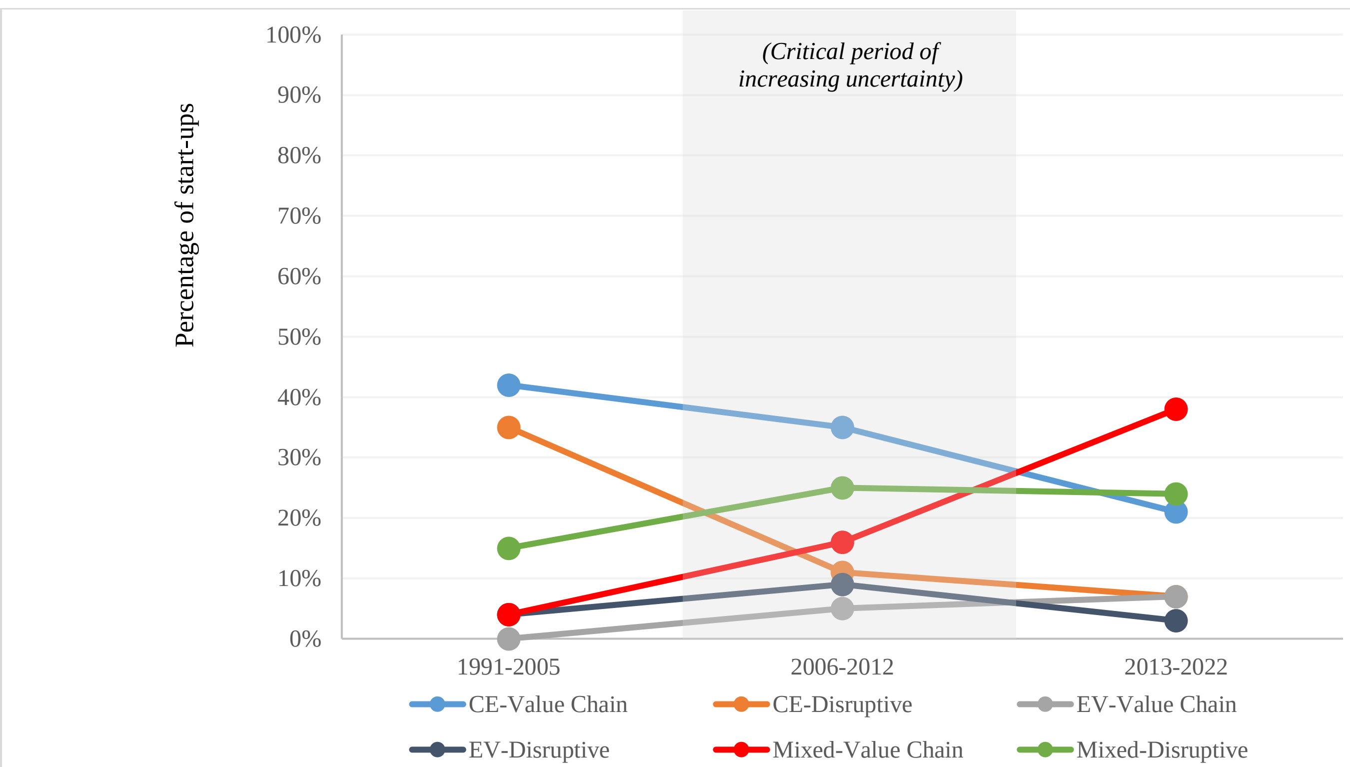

Figure 3-6 Graphical representation for the summary statistics in Table 3-1.

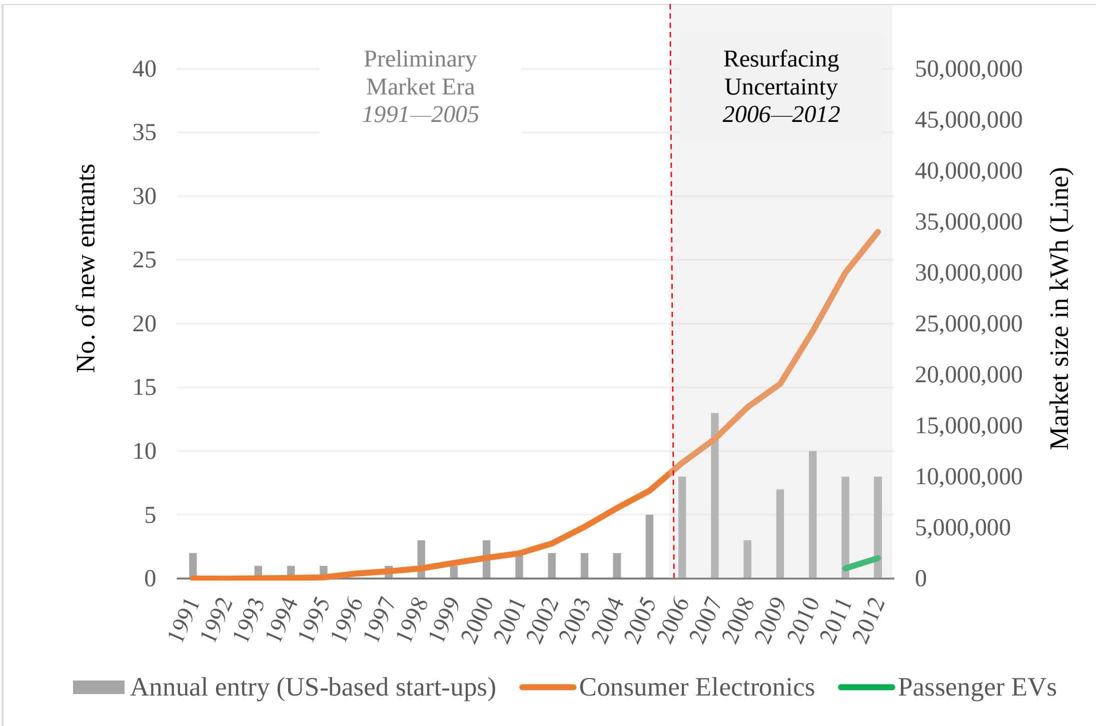

Figure 3-7 Market size of Li-ion batteries in the markets for consumer electronics and electric vehicles during the Resurfacing Uncertainty period.

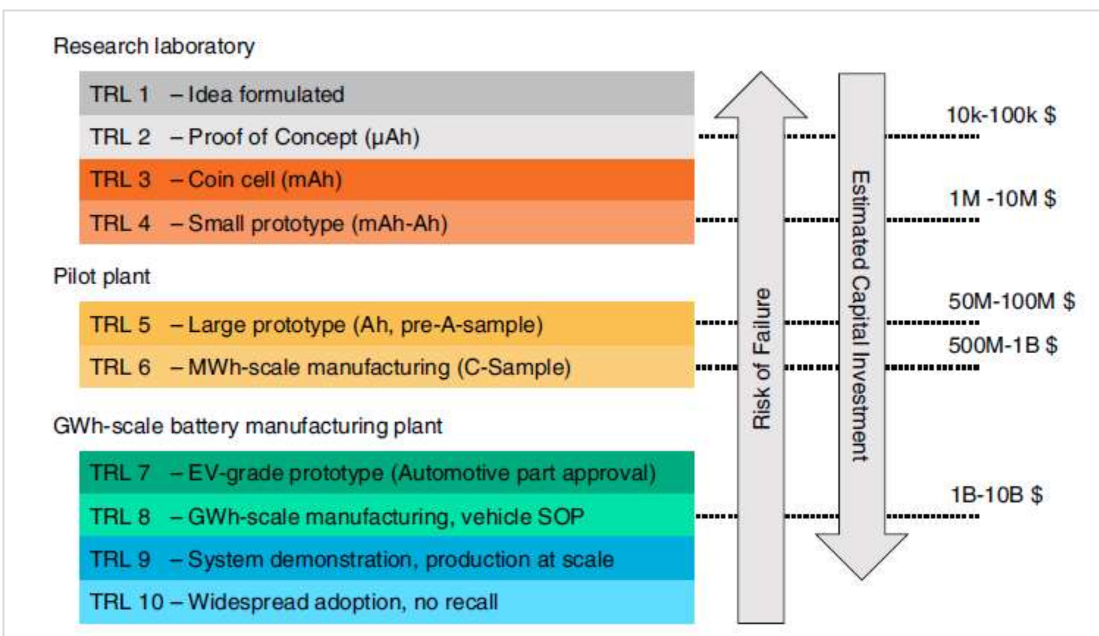

Figure 3-8 Technology Readiness Level (TRL) scale for developing and commercializing lithium-based battery technology for the electric vehicle market. *Source:* Frith et al. (2023).

Table 3-2 Summary statistics for the average number of US dollars in millions (early-stage VC & grants) invested into battery start-ups based on their choices of application market & entrepreneurial strategy at entry (3-year average after founding year).

	Choice of entrepreneurial strategy					
	1st period 1991—2005		2nd period 2006—2012		3rd period 2013—2022	
Choice of application market	(1) Value Chain	(2) Disruptive	(3) Value Chain	(4) Disruptive	(5) Value Chain	(6) Disruptive
Both *Mixed uncertainty*	n/a	6.75	7.85	20.48	9.05	16.66
Electric Vehicle *High uncertainty*	-	n/a	8.58	4.65	25.85	6.22
Consumer electronics *Low uncertainty*	1.08	12.60	4.10	1.26	0.89	12.48
Total $ Funding raised	152		496		719	
Total no. of start-ups	26		57		68	

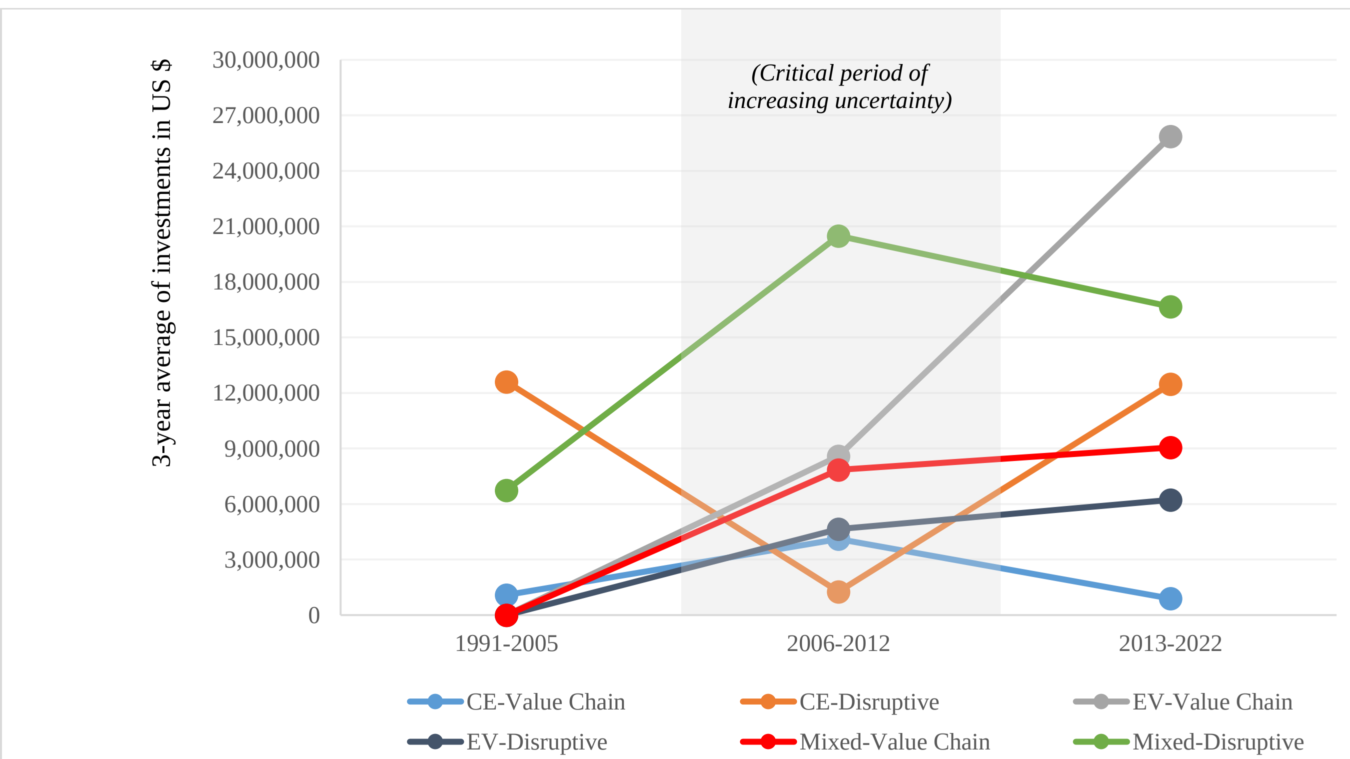

Figure 3-9 Graphical representation for the summary statistics in Table 3-2.

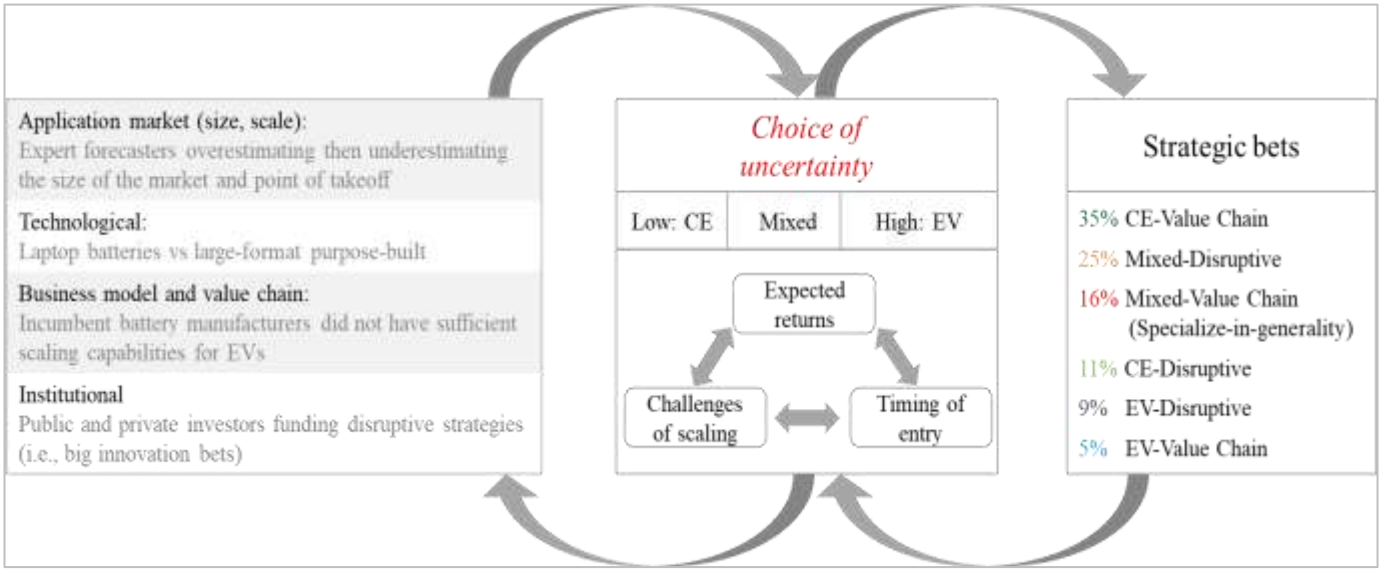

Figure 3-10 Conceptual framework for possible explanation (5): Resurfacing Uncertainty.

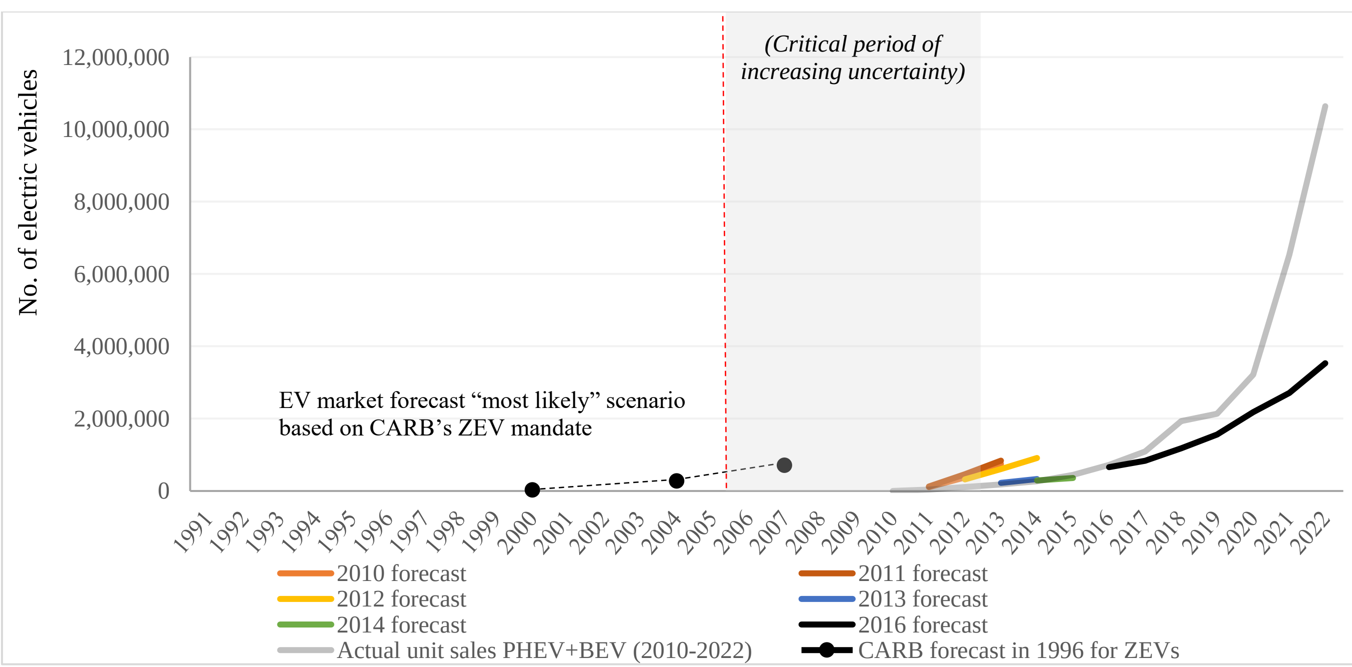

Figure 3-11 Forecasts vs actual market growth of unit sales of electric vehicles (i.e., deviation from reality)
Source: Mader, 1996 (CARB forecast); BloombergNEF 2010—2016 (forecasts) and 2010—2022 (actual).

Appendix

Table A-1 Keyword search in firm Business Description as reported in S&P Capital IQ database.

Search	Search Criteria
1.	Keyword: "Lithium" OR "li-ion" OR "lithium-ion" OR "lithium ion" OR "Solid-state" OR "Solid state" OR "lithium polymer" OR "lithium iron" OR "cathode" OR "anode"

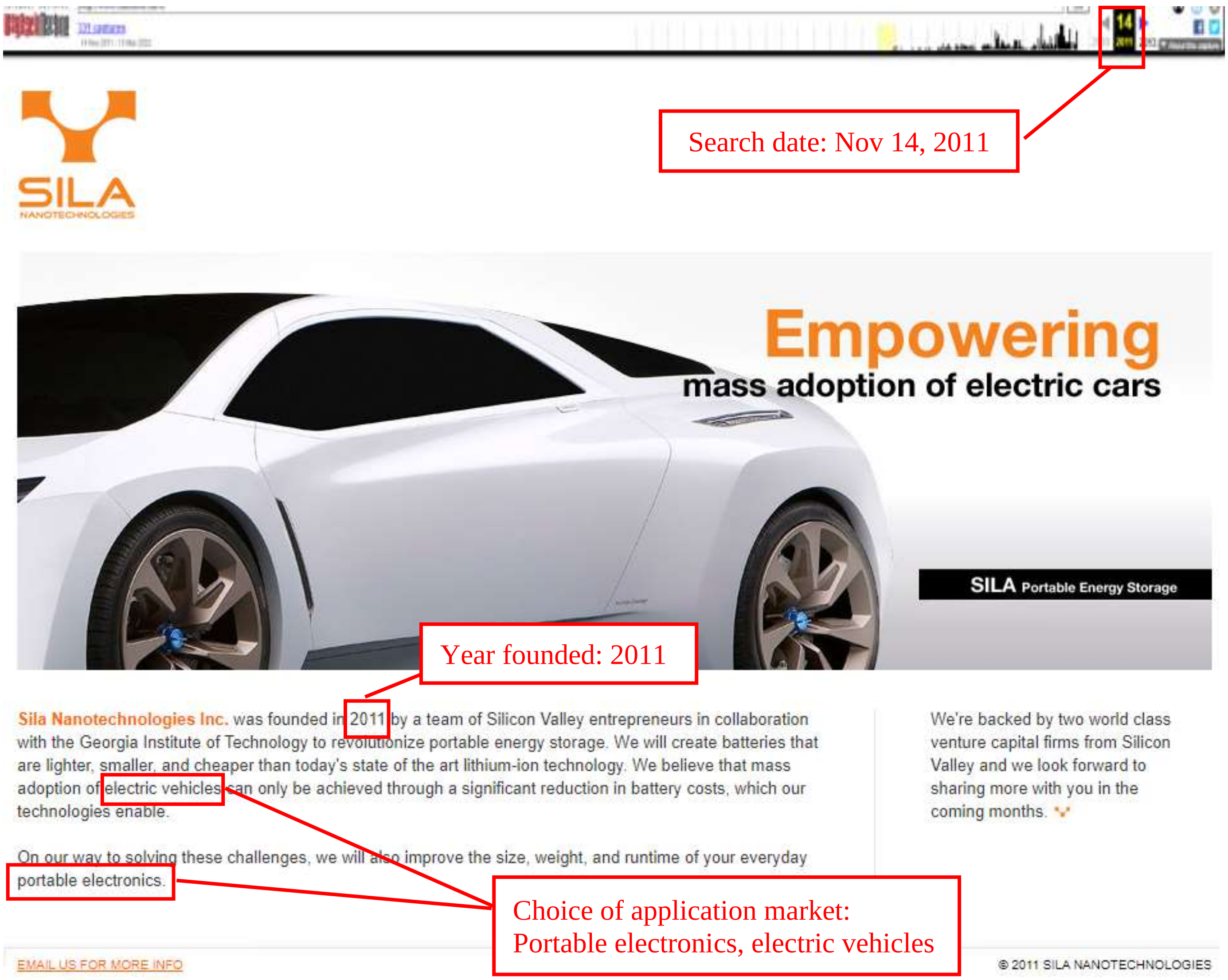

Figure A-1 Data collection from the official website of a battery start-up (i.e., Sila Nanotechnologies) in the WayBack Machine.

Amount:	Phase:	Program:
$225,000.00	Phase I	SBIR

Solicitation Topic Code: 1

Solicitation Number: N/A

Timeline

Solicitation Year:	Award Year:	Award Start Date (Proposal Award Date):	Award End Date (Contract End Date):
2012	2012	2012-10-01	2013-02-28

Small Business Information

SILA NANOTECHNOLOGIES, INC.

541 10th St NW #195
Atlanta , GA 30318-
United States

DUNS:
78319503

HUBZone Owned:	Woman Owned:	Socially and Economically Disadvantaged:
No	No	No

Principal Investigator	Business Contact	Research Institution
Name: Gene Berdichevsky Title: CEO Phone: (404) 919-7452 Email: gene@silanano.com	Name: Gene Berdichevsky Phone: (404) 919-7452 Email: gene@silanano.com	N/A

Abstract

To accelerate the adoption of battery electric vehicles (BEVs), Sila Nanotechnologies and its project team aim to transform portable energy storage by demonstrating 1200 Wh/L performance in full cells, with electrode materials materials cost of just $40/kWh. By more than doubling the amount of energy stored in any given form factor cell, without changing the manufacturing process, we will reduce the cost to produce a kWh of storage in half. In order to achieve these goals, Sila will abandon conventional intercalation materials such as LiCoO2 and C, in favor of an alloying-type materials pair using lithium disulfide (Li2S)-based composite cathode, and silicon (Si)-based composite anode. Both of the proposed materials will be synthesized into proprietary structures developed at Sila and Georgia Tech and tested in fully functioning, 1Ah+ cells.

* Information listed above is at the time of submission. *

Choice of Li-ion battery technology: Component - silicon-based anode

Figure A-2 Data collection from an approved grant in the SBIR/STTR programs for a battery start-up (i.e., Sila Nanotechnologies).

History of the Lithium-ion battery industry

1973—1990 Incubation: Energy crisis, scientists, & scientific breakthroughs

The popularity of Li-ion battery research and development could be traced to different triggers. It could be argued that it was the oil crisis in the 1970s that motivated experimentation efforts by researchers and investments by energy corporations towards oil alternatives and new energy sources (Sine and Lee, 2009). Or, it could have been simply scientific curiosity that drove such research and investment efforts. Regardless of the initial triggers during the industry's incubation period (Moeen and Agarwal, 2017), in retrospect, the discoveries of three scientists (Stanley Whittingham, John Goodenough, and Akira Yoshino) have shaped the foundational base of scientific knowledge for the first commercialized Li-ion battery technology. In 2019, the three scientists earned the Nobel prize for their significant contributions to the development of the Li-ion battery. Important to note that ever since the first rechargeable battery was invented in 1799 ("voltaic pile" by Alessandro Volta), essentially every battery is comprised of four key components, "two electrodes – an [1] *anode* and a [2] *cathode* – dipped in a conductive solution (called an [3] *electrolyte*) with a [4] *separator* that controls the flow of the electric charge" (Rathi, 2019).

In 1976, chemist Stanley Whittingham, with a research group at Exxon, demonstrated the first instance of a rechargeable Li-ion battery by combining lithium metal (Li-metal) anode and titanium sulfide (TiS) cathode (Whittingham, 1976). Given the chemical properties of the battery's combined components, the applicability of Whittingham's Li-ion battery was limited to coin cell level batteries applicable for watches (Mizushima et al., 1980). During the late 1980s, Whittingham's battery prototype faced more problems by instances of battery fires, such as those experienced by Moli Energy Ltd. (Vancouver, Canada) in cell phones, which further discouraged the commercial use of such Li-metal batteries. At the same time, the oil crisis was ending (in 1980) and energy companies like Exxon suspended its battery research. Whittingham's workable battery prototype and other battery research have sparked wider research interest in further developing next generation battery technology. In 1980, physicist John Goodenough, at the University of Oxford, and colleagues discovered a new type of cathode; lithium-cobalt-oxide (LCO) (Mizushima et al., 1980). They found that by replacing the previous titanium sulfide cathode with LCO cathode (commonly used today in Li-ion batteries for consumer electronic devices) would result in a battery technology that was safe, stored more energy, and provided more freedom for the choice of anode material (Li et al., 2018). Thereafter, in 1985, chemist Akira Yoshino, while working at the chemicals company Asahi Kasei (Japan), discovered that replacing the Li-metal anode with petroleum coke (a type of carbon material) considerably reduced fire risks of the battery. Thus, Yoshino paired his anode with Goodenough's LCO cathode and the other battery components (i.e., separator, electrolyte, and other additives), and patented the Li-ion battery technology that laid fundamental elements of the first commercialized Li-ion battery (Yoshino et al., 1987). Eventually in 1991, Yoshio Nishi (expert in electrolytes and carbon materials in batteries), Ozawa Kazunori (expert in coating from the magnetic tape division), while working at Sony Corporation (Japan), and coworkers have aggregated the prior scientific breakthrough knowledge into the first commercial mass-producible Li-ion battery technology by Sony Corporation that enabled them to introduce a smaller and lighter consumer product: the TR1 8mm camcorder (Nishi, 2001; Blomgren, 2016).

1990—1998 Commercialization: Government initiatives, early pioneers, & initial product markets

In the early-1990s, despite the early efforts by large Japanese corporations in scaling production of Li-ion batteries specialized for consumer electronics, the US government has pointed the automotive and energy sectors towards the need of developing and funding electrochemical energy storage technologies that would support the commercialization of electric vehicles. Notably in 1990, California Air Resources Board (CARB) pioneered the Zero-Emission Vehicle (ZEV) mandate, which required incumbent auto manufacturers' new vehicles sold in California market include 2% ZEVs in 1998, 5% ZEVs in 2001, and 10% ZEVs in 2003. To find viable solutions that met the requirements of the ZEV mandate, the US Advanced Battery Consortium was formed as a cooperative initiative between industry and government. The major partners included Chrysler, Ford, General Motors (GM), Electric Power Research Institute (EPRI), and the Department of Energy (DOE).

Shortly after Sony successfully commercialized the Li-ion battery for its camcorders in 1991, Asahi Kasei and Toshiba formed a partnership (A&T Battery Co.) that resulted in commercializing the first Li-ion powered laptop (Toshiba Portege T3400CT) in 1993. Around the same time, Compaq's less expensive portable computer, Contura Aero, was still powered by nickel-metal hydride (NiMH) batteries (Mossberg, 1994). Among the physical and chemical properties of a Li-ion battery, the notion of an electrochemical device that was lighter in weight and packs more energy in a smaller space had significantly differentiated Li-ion batteries from the incumbent rechargeable battery technologies; nickel-cadmium (Ni-Cd) and NiMH for consumer electronic products (Jaffe, 2013). In 1994, Motorola commercialized the first Li-ion powered cell phone; the MicroTac Elite. The commercialization of the Li-ion battery demonstrated instant success in consumer electronics, in which Sony sold 3 million units and 15 million units in 1993 and 1994, respectively (Rathi, 2019). *So, what were the foundational principles of manufacturing Li-ion batteries at scale?*

It also happened to be that Sony was also a major manufacturer of cassette tapes. As the market for compact discs (CDs) started to become popular in the 1990s, the market for cassette tapes started to erode. So, Sony ended up repurposing the idle manufacturing lines, which were specialized for cassette tapes, to produce Li-ion batteries (LeVine, 2015). Similar techniques were utilized, i.e., coating slurry onto a film, then drying and cutting it, but instead of magnetic tape it was used to process battery electrodes. Thus, those principles of manufacturing Li-ion batteries at scale and technicians "became the backbone of the world's first lithium-ion battery manufacturing plant, and the model for how they have been made ever since" (LeVine, 2015).

During the early 1990s, Li-ion battery technology was the most expensive among other types of rechargeable batteries, yet its potential applicability quickly gained popularity across different consumer electronic producers because it enabled them to introduce lightweight portable devices that had more energy and runtime. By the mid-1990s, as the demand for Li-ion-powered consumer electronic products (i.e., cell phones and laptops) increased, it incentivized further experimentation efforts aimed at advancing the performance of Li-ion batteries and increased its production by large battery manufacturers. Notably in 1996, Professor John Goodenough, Akshaya Padhi, and coworkers had discovered a new type of cathode electrode for Li-ion batteries – Lithium iron phosphate (LFP) (currently being supplied by CATL for Tesla's Model 3).

Towards the late 1990s, auto manufacturers started rolling out prototypes and commercially available electric vehicles in compliance with the ZEV mandate. For instance, GM EV-1 (powered by lead acid), Ford Ranger EV (powered by lead acid and then NiMH), Toyota RAV 4 (powered by NiMH), Honda EV Plus (powered by NiMH), Chrysler EPIC (powered by NiMH), and Nissan Altra (powered by Li-ion manufactured by Sony). Thus, it seemed that while Li-ion batteries were gaining popularity in consumer electronic product markets, it was not a clear strategic choice of battery technology to be used for electric vehicles. Arguably, the high-cost of Li-ion batteries would have forced auto manufacturers to offer a higher price tag for its electric vehicle, which was not an appealing proposition for the mass-market when compared with that of gasoline-powered vehicles. Such consumer demand uncertainty could have exacerbated given the early-stage of the market for electric vehicles; a more complex technological product compared to small-sized consumer electronic products. For example, while the GM EV-1 that packed lead acid batteries was priced at $33,959, the Nissan Altra that packed Li-ion batteries was priced at $50,999 (Chan, 2002). Therefore, most auto manufacturers chose to experiment with lower cost incumbent battery technologies (i.e., lead acid, NiMH). Another factor that would have further discouraged the wider adoption of electric vehicles was related to the infrastructure of charging stations. Consumers of electric vehicles would not have benefited from widely available filling stations as those that were developed for gasoline vehicles over nearly a century.

For the first decade since Li-ion was first commercialized, while large Li-ion battery manufacturers, like Sony, Sanyo (Japan), Mitsubishi Electric Co., Ltd (Japan), were mass producing Li-ion batteries solely for consumer electronic products, US Li-ion battery start-ups, like T/J Technologies and PolyStor Corporation were founded on the basis of a battery cell-level innovation (i.e., component: cathode or cell design), intended to create value for batteries in consumer electronic products and capture value by trading in markets for technology (i.e., intermediate markets). Thus, it was not surprising that during this period, there was no sign of any battery manufacturer that produced Li-ion batteries or designated its production lines for the electric vehicle market, since most of the demand for Li-ion batteries increased alongside the growing market for consumer electronic products, mostly for laptops and cellphones (note: Amperex Technology Limited (ATL) – today known as CATL – was founded in 1999 to produce Li-ion batteries for consumer electronic products and did not produce Li-ions for electric vehicles until 2011).

1998—2008 Broadening market scope: Seeding the applicability of Li-ion battery for electric vehicles

Although Li-ion batteries did not seem like a strategic choice of battery technology for incumbent auto manufacturers to be placed in electric vehicles, it did seem that incumbent battery technologies (i.e., lead acid and NiMH) and the new Li-ion battery were all possible battery technology options that could have been used to electrify electric vehicles. Yet, in the early 2000s, auto manufacturers persisted in pushing back on the 2003 ZEV mandate's target by citing the continual lack of breakthroughs in battery technology, high costs, and lack of consumer interests (McConnell et al., 2019). By 2003, CARB modified the ZEV mandate, which could be argued that such modification acted against the efforts that advocated for more all-electric vehicles. More specifically, under the revised ZEV mandate, auto manufacturers were no longer required to produce all-electric vehicles but instead were required to produce a mix of fuel cell vehicles, hybrid vehicles (i.e., gas-electric powered vehicles), and partially-zero-emission vehicles by 2008. As a result, by the mid-2000s, auto manufacturers (i.e., GM, Ford, Honda, and Toyota) started pulling their fleets of leased and commercialized electric vehicles off the road (see Paine, 2007 for documentary).

While the incumbent auto manufacturers pivoted away from producing all-electric vehicles towards hybrids (i.e., Honda Insight, Toyota Prius), US battery start-ups, like A123 Systems (founded in 2001), were founded on the idea of advancing Li-ion battery technology for downstream product markets (initially for consumer electronics and later included electric vehicles). At the time, another notable start-up was AC Propulsion, founded by Alan Cocconi, a company that specialized in developing drivetrain systems for the electric vehicle market. In 2003, AC Propulsion introduced their drivetrain system in the upgraded version of their electric vehicle prototype, the T Zero sports-car, which was powered by battery packs that consisted of 6,800 Li-ion battery cells like those used in laptop computers – an experiment that was commissioned by technology entrepreneur Martin Eberhard (Shnayerson, 2007; Higgins, 2021). Compared to the original version of the T Zero, which was powered by heavy lead acid batteries, the Li-ion-powered T Zero had lighter weight, more range, and greater overall driving performance. Yet, transforming the company into an auto manufacturer was not a path forward for AC Propulsion's founder Alan Cocconi. Thus, AC Propulsion had other interests, which involved developing drivetrain systems for electric vehicles. In doing so, their business model was more about trading with auto manufacturers in markets for technology or retrofitting affordable gasoline vehicles, such as the Toyota Scion, into an electric vehicle and selling them. Therefore, in 2003, technology entrepreneurs Martin Eberhard and Marc Tarpenning co-founded Tesla Motors. The entrepreneurs' main strategic objective of founding Tesla Motors was to push forward the spirit of the T Zero into production that would result in the commercialization of an electric vehicle – the Tesla Roadster. Furthermore, starting a car company would be hugely capital-intensive. At the time, it was not an investment that seemed to attract venture capitalists, especially when there had not been a successful new car company for generations (Higgins, 2021). The Tesla founders' initial critical constraint was to raise millions of dollars to fuel its production processes. When they were able to eventually secure their initial funding round, totaling $6.5 million (including $6.35 million from Elon Musk), Tesla's subsequent constraints were more technical: modifying the Li-ion battery pack, electric motor, and finalizing the overall design for commercialization. In fact, bringing their first model – the Tesla Roadster – to market will enable the company to establish supplier relationships to outsource the required components and attract additional funding in subsequent rounds to fuel their production operations. Although the T Zero was an initial proof-of-concept for a Li-ion powered electric vehicle with high driving performance, it needed further modifications before it could be a viable electric vehicle to go into production.

While the increasing adoption rate of Li-ion battery technology was exemplified in the growing consumer electronic product markets, it did not seem to be a viable battery technology for mass adoption in the electric vehicle market. Such tensions of adopting Li-ion in the electric vehicle market was exacerbated when the US consumer electronics industry underwent the largest safety recall due to Li-ion battery fire incidents in laptops. For instance, between 2004 and 2005 Apple Inc. recalled 150,000 laptops that contained Li-ion batteries, which were supplied by LG Chem (Korea). Similarly, in 2006, Dell recalled 4 million laptops that contained Li-ion batteries, which were supplied by Sony. Those battery fire incidents were traced to either manufacturing defects or inefficiencies in the battery management systems that resulted in battery overheating. The incidents raised serious safety concerns that resided in the Li-ion battery manufacturing industry. Those safety concerns further discouraged battery manufacturers, like LG Chem or Panasonic, from wanting to sell or be associated with any electric car start-ups or even incumbent auto manufacturers to use their batteries for powering electric vehicles (Kelty, 2020; Higgins, 2021). At that time, the electric vehicle market was viewed as a risky play for incumbent battery manufacturers, such that if Li-ion batteries were handled poorly it would have severely raised potential legal and reputational liability for battery manufacturers (Kelty, 2020).

By mid-2000s, on a global market scale, not only did Li-ion batteries accounted for 75% of the rechargeable-battery business, but also newer variations of the Li-ion battery technology delivered significantly more power, evolved into the power tools market, and gained a broader interest across other product markets, such as vacuum cleaners, ride-on lawn mowers, and hybrid automotive vehicles (Bulkeley, 2005).

Thus, it seemed that as incumbent battery manufacturers were not designating their production lines to producing Li-ion batteries for the electric vehicle market, it could have incentivized battery start-ups (i.e., A123 Systems, Advanced Battery Technologies, Farasis Energy) to bring their advanced Li-ion battery technology (whether a component or battery product) to market that was targeted for the consumer electronics, electric vehicles, or both. In addition, between the mid- and late-2000s, there was a influx of increasing battery start-up entrants, venture capital and corporate investments, and government grants in the space of US clean energy technologies.

2008—2012: Tesla movement & the electric vehicle market

In efforts to encourage auto manufacturers to produce more electric vehicles and increase their adoption rate on the consumer side, the US government passed the Energy Improvement and Extension Act of 2008 that granted tax credits for new qualified plug-in electric vehicles. Thus, the government was not only motivating the innovation of clean technology on the supply-side, through its grant programs, but also incentivizing end-consumers to transition towards the adoption of electric vehicles. Furthermore, in 2009, the US government also passed the American Recovery and Reinvestment Act (ARRA) and American Clean Energy and Security Act (ACES) that allocated $2.4 billion to support the development of next-generation batteries, electric vehicles, smart grid technology and infrastructure.

After struggling to overcome many of its technical constraints regarding its proprietary electric powertrain system -- the batteries and motor, Tesla started delivering its first electric vehicle (Tesla Roadster) to its customers in 2008. By 2012, Tesla had delivered approximately 2,450 Roadsters to customers in over 30 countries

(Tesla Motors, 2012). Yet, the Tesla Roadster was priced approximately more than double its original target price of $49,000 (Higgins, 2021). At the same time, the competition among US Li-ion battery start-ups had intensified, where each strived to establish partnership deals with battery manufacturers in intermediate markets and/or auto manufacturers in downstream product markets. For battery start-ups to secure supplier partnership agreements signaled the potential applicability of their battery innovation. In 2009, A123 Systems (Li-ion battery start-up) had the biggest IPO where its shares soared 50% on opening day. At the time, A123 Systems did not only partner with Black and Decker to supply Li-ion batteries for power tools but also established partnership agreements with incumbent and start-up auto manufacturers (i.e., GM, Th!nk, Shanghai Automotive, Chrysler, Fisker Automotive) to eventually supply their batteries to the electric vehicles market. Such an IPO might have generated excitement for the Li-ion battery industry, yet it was not clear if it was a successful outcome for the start-up or simply a strategic fundraising technique to be able to scale its operations until the demand for the emerging electric vehicle market takes-off. On the other hand, Tesla's success for its Li-ion battery system in its Roadster started to attract more interest from incumbent battery manufacturers (i.e., Sanyo, Panasonic) and auto manufacturers, such as Daimler (Germany) and Toyota (Japan). On the battery industry side, Tesla's battery technology director, Kurt Kelty was able to eventually strike a supplier agreement for battery cells with his previous employer, Panasonic (Kelty, 2020; Higgins, 2021). While on the auto industry side, Daimler and Tesla worked out a supplier relationship agreement in which Tesla would supply electric powertrain components (i.e., Li-ion battery packs) to Daimler to create an electric version of their Smart car for the US market. Subsequently, in early 2010, Tesla was able to secure a similar deal with Toyota for its RAV4 compact sport utility vehicle. Although Tesla's initial vision was not merely to become a Li-ion battery system supplier for incumbent auto manufacturers. Yet, such corporate investments seemed to be an opportunity for Tesla to bolster its value for its investors, and to secure more capital that will enable them to scale production of their next electric luxury vehicle project -- the Model S -- that the company planned to manufacture thousands a year. In June 2010, although there were both speculations and excitement regarding Tesla Motors shares rising nearly 41% higher on its first day going public, it marked as an intriguing market event for the Li-ion battery technology for the emerging electric vehicle market. Furthermore in 2011, Contemporary Amperex Technology (CATL), a Chinese battery manufacturer for consumer electronic product markets, started to designate production lines for manufacturing Li-ion batteries for the emerging electric vehicle market.

While Tesla, a start-up car company, was pushing forward the development and commercialization of plug-in all-electric vehicles, incumbent auto manufacturers like GM introduced one of the first plug-in electric hybrid vehicles – Chevrolet Volt – powered by Li-ion batteries that were sourced from incumbent battery manufacturer LG Chem. By 2012, Toyota also introduced the newer version of its Prius plug-in electric hybrid vehicle that was packed with Li-ion batteries (previous Prius models were powered by NiMH batteries). Similarly in China, BYD (at that time second largest Li-ion battery producer) had also generated excitement for Li-ion batteries by selling hybrid electric vehicles powered by Li-ion batteries. The intensified research and development efforts (i.e., patenting activity) by Li-ion battery start-ups and incumbents for the electric vehicle market have resulted in different variations of Li-ion battery technologies with no clear choice for a winner-take-all battery technology.

2012—2023: Start-up exits, rise of the Giga-Factory, & sales takeoff in the electric vehicles market

By the mid-2010s the demand for Li-ion batteries continued to increase in the well-established consumer electronic market and incrementally increased in the emerging electric vehicle market. Yet, US Li-ion battery start-ups were facing considerable challenges in developing the manufacturing capabilities that would enable them to produce their battery innovation at a scale that would make them a profitable business. In addition, venture capitalists realized that although Li-ion battery innovations seemed to be an attractive clean technology investment, a workable battery technology is completely different from establishing a mass-producible battery technology. Venture capitalists also realized that battery companies do not operate according to their three- to five-year model for return on investments. Especially when most of the battery manufacturing capabilities at scale were dominated by incumbent battery manufacturers, such as Panasonic (Japan), BYD (China), and LG Chem (Korea). Amid those challenges, the market for electric vehicles was not increasing as forecasted. The battery scaling challenges and the market demand uncertainty for electric vehicles were exemplified in 2012, when US battery manufacturer A123 Systems was forced to file for bankruptcy that led to its acquisition by the Chinese automotive components manufacturer Wanxiang Group. Such a battery start-up exit subsequently forced the start-up car company for electric vehicles, Fisker Automotive, to suspend its production.

As the applicability of Li-ion batteries expanded into commercial aircraft, such an application market for Li-ion batteries also faced technical battery problems, similar to the fire incidents in consumer electronic laptops in the mid-2000s. For instance, in 2013, Boeing's fleet of 787 Dreamliners was grounded due to electrical system problems stemming from its Li-ion batteries. More specifically, the malfunction of the onboard Li-ion batteries, which were supplied by GS Yuasa Corporation (Japan), was caused by thermal runaway – a condition when heat from a failing battery cell causes itself and surrounding battery cells to fail, thus generating more heat. In 2014, amid the apparent scale and cost complexities involved in manufacturing Li-ion batteries, the electric vehicle pioneer, Tesla, and incumbent battery manufacturer, Panasonic, signed an agreement to build a large-scale Li-ion battery manufacturing plant in the US – known as the Giga-factory – for Tesla's electric vehicles and stationary storage market.

Important to note that reduction in cost per unit of electric energy (kilowatt hour, kWh) for Li-ion batteries was possible by either improving the process of mass-production of batteries or by a Li-ion battery breakthroughs within its sub-components (i.e., cathode, anode, electrolyte, separator) that would increase the energy density (kWh) without a significant increase in cost. By 2016, 43% of all manufactured Li-ion batteries are represented by demand in the electric vehicle sector (pure electric, hybrids, electric buses) and forecasted to be ~50% in 2025. It could be argued that enhancing Li-ion battery performance and significant cost decreases have led to its applicability across broader product markets. Yet, it requires to unfold the context-specific actors and their strategic choices to better understand the causes of market transformation for the Li-ion battery technology, which eventually led to its potential applicability across broader downstream product markets and its sales takeoff in the growing electric vehicle market.

Role of economic actors in shaping market transformation

Enabling technologies are peculiar in the sense that they can span across and transform various product markets, yet such a transformative process can be identifiable in retrospect. *Then, how did different types of firms play a role in the market transformation process?* Historical analysis revealed that, after Sony commercialized the first Li-ion battery for its camcorders, the vast production of Li-ion battery cells was primarily dominated by Japanese companies for the consumer electronics market. Yet, in the US, there was a host of entrepreneurial start-up firms that entered with different battery innovations intended to advance the Li-ion battery technological system. Such innovations mapped onto different levels of the Li-ion battery technological system: battery cell subcomponents, cell design, cell manufacturing processes. In other words, battery start-ups that entered the landscape of advancing upstream battery cell technology or its sub-technologies played a critical role in infusing cutting-edge technologies that are valued in downstream intermediate or product markets. In other words, innovators of upstream technologies set the technical performance boundaries for downstream products (Adner and Kapoor, 2010).

Analysis of the early global Li-ion battery manufacturers

Throughout the first decade since the commercialization of the first Li-ion battery, the battery production was primarily dominated by companies in Japan.

Shortly after the success of Sony's Li-ion powered camcorder (TR1 8mm), other incumbent battery manufacturers decided to develop and produce Li-ion batteries. For instance, Matsushita Electric Industrial (renamed Panasonic Corporation in 2008), which was founded in 1918, positioned itself as a Li-ion battery manufacturer for consumer electronics in 1994. Around the same time, Sanyo Electric Co. (acquired by Panasonic in 2009), which was previously producing rechargeable NiMH batteries, also began manufacturing Li-ion batteries for consumer electronics and became one of the largest global manufacturers for Li-ion battery cells.

Similarly, in China, BYD Co. (founded in 1995) entered as a manufacturer of rechargeable batteries, including Li-ion batteries for consumer electronics. By the early-2000s, BYD also became one of the largest global manufacturers of Li-ion batteries for mobile phones to companies like Motorola, Nokia, and Samsung Electronics. In addition, Tianjin Lishen Battery Co., was another Li-ion battery manufacturer that entered the industry in 1997. Like the other Li-ion battery manufacturers during that time, Tianjin Lishen Battery Co. also produced Li-ion batteries for the mobile phones market and formed strategic partnerships with Motorola and Philips.

Lastly, companies located in South Korea were also among the early entrants that quickly developed into large Li-ion battery manufacturers. For instance, Samsung, as a well-known global leader for producing consumer electronics, started developing and producing Li-ion batteries in 1999. At the same time, LG Chemical, as the largest South Korean chemical company, began mass production of Li-ion batteries targeted for consumer electronic products.

Thus, most of the Li-ion cell manufacturing was based in Asia. In fact, by 2010, rechargeable battery manufacturers in Japan, South Korea, and China still accounted for more than almost 95% of global cell manufacturing with approximately 67% of produced batteries were for cellular phones (31%), portable PCs (28%), and power tools (8%) (Pillot, 2010). Important to note that the largest Asian battery manufacturers were vertically integrated OEMs (Original Equipment Manufacturers) of downstream consumer electronic products. For instance, the previously mentioned companies; Sony, Panasonic, Sanyo, BYD, Samsung, and LG Chem, either started in the consumer electronics industry and vertically integrated upstream in the Li-ion battery production industry or entered upstream as a battery manufacturer and then vertically integrated into producing downstream consumer electronic products. Thus, the geographical proximity between battery production and consumer electronic product manufacturing offered a competitive advantage for those large Asian companies in developing new consumer electronic products (Brodd, 2005).

Analysis of US-based Li-ion battery start-ups

While the largest battery manufacturers in Asia (Japan, South Korea, China) dominated large-scale production of Li-ion batteries for consumer electronic product markets, US Li-ion battery start-ups were engaged in commercializing cutting-edge battery technology that were, conventionally, either traded in intermediate markets or integrated into Li-ion battery manufacturing firms through acquisition. Interestingly, by the second decade, since the first commercialization of the Li-ion battery, and as the interest of Li-ion batteries surged in the electric vehicle market, a growing number of US battery start-ups emerged as component innovators and gradually integrated into a battery system integrator for downstream product markets or just specialized as upstream battery subcomponent innovators/manufacturers. Although all US battery start-ups remain as small players compared to the large battery manufacturers in Asia, their Li-ion battery technology has attracted much attention from both incumbent battery manufacturers as well as OEMs in the consumer electronics and electric vehicle market through strategic partnership/alliance or acquisition deals. Even more so, as the electric vehicle market is in its emerging stages, battery incumbents do not have the advantage of a vertically integrated organizational structure as they initially had for the consumer electronic products (except for BYD in China that produced its own battery system for its plug-in hybrid electric vehicle). In other words, they lacked the development and manufacturing capabilities in the downstream electric vehicle market. Since the Li-ion battery manufacturing industry for the electric vehicle market is still in its growing stage, not being vertically integrated OEMs could benefit from emerging battery technologies such as, silicon-based Li-ion batteries or solid-state Li-metal batteries. Each battery technology comes with its distinct battery cell performance metrics that is considered as a key competitive advantage for downstream product manufacturers.

Table A-2 Business history on 10 US-based Li-ion battery start-ups.

Firm name	Technology capability	Targeted-product markets	Value Capture Events	Status
PolyPlus Battery Company Inc.	**1991:** founded based on inventing (lithium/organsulfur) battery at Lawrence Berkeley National Lab. **2000:** Invents protected lithium electrode (Li-metal electrode) **2017:** Introduces glass protected Li-metal batteries (innovation for Li-anodes).	**2005:** Li-air, Li-water, Li-sulfur batteries.	**2005: BM:** IP development and Licensing chemistry.	**2023:** operating
T/J Technologies	**1991:** founded **1996:** developer of electrode materials (cathode, anode). **2003:** Lab scale quantities of performance materials.	**1996:** Ultracapacitors, Li-ion, fuel cells **2001:** portable electronics, stand-by power systems, motor vehicles, defense/aerospace, hybrid electric vehicles.	**1996: BM:** strategic alliances/partnerships. **1997:** Partnership-Lockheed Martin for defense business. **2003:** Awarded 3 NASA contracts for advanced materials research. **2005:** Awarded contract to develop batteries for Air Force Launch vehicles **2005:** Awarded contract to develop batteries for naval weapons	**2006:** acquired by A123 Systems
PolyStor Corporation	**1991:** founded based on battery technology developed at Lawrence Livermore National Laboratory. **1997:** developer of 18650 Li-ion battery cells. **1997:** Purchase order with Sony & Itochu for Li-ion battery assembly line. **1998:** manufacturer of 18650, prismatic Li-ion batteries, chargers, packs. **2000:** Granted license to portion of Motorola ESG's Li-ion polymer technology.	**1997:** consumer electronics (Portable, notebooks, PDA, PDT, Cellular phones, mobile radios, Mini/compact disc, camcorders). **1998:** consumer electronics, EV, aerospace. **2000:** consumer electronics, e-bikes and scooters, hybrid and full Electric Vehicles, aerospace, UPS and military	**1997: BM:** partnership with OEMs. **1998:** USABC contract to develop battery system for HEV. **1999:** alliance with LinkSol for exclusive distribution in Asia Pacific region.	**2002:** out of business
Quallion	**1998:** founded **2001:** developer of battery cells and systems. **2008:** developer of materials, cells, packs. **2009:** built a battery plant in California.	**2001:** medical(neurobionics), aerospace, electric vehicle, military, other specialty fields. **2008:** medical, military, space/ aviation, HEV/ EV, PHEV, others.	**2009:** Awarded Boeing contract to retrofit emergency battery power supply. **2011:** Navy launches satellite with Quallion Li-ion.	**2013:** acquired by Enersys
A123 Systems	**2001:** founded based on licensed patents from MIT. **2001:** developer of electrode (cathode). **2005:** developer of materials, cells, modules.	**2001:** laptop, cell phone, PDA. **2005:** power tools, HEV, home appliances, electric drive systems, robotics, stationary power, load balancing, military, medical devices. **2009:** transportation (hybrid electric, plug-in hybrid, electric vehicle, heavy	**2005:** alliance-DeWalt's Black & Decker for power tools. **2007:** partnership-Cobasys (develop HEV battery systems), BAE	**2009:** IPO **2012:** bankruptcy **2013:** acquired by Wanxiang

	2011: developer of materials, cells, modules, packs	duty, aviation), portable power, grid stabilization, military devices	Systems, GM (develop Li-ion cells for Chevy Volt). **2008:** partnership-Th!nk (develop batteries for EVs), AES (develop for ESS). **2009:** partnership-Shanghai Motive (HEV), Chrysler (ENVI EV). **2010:** partnership-Fisker (battery system supplier), Navistar (battery system development), Eaton (HEV trucks). **2012:** partnerships-Via Motors, BMW, Tata Motors, McLaren, Geely.	Group Corporation
Infinite Power Solutions	**2001:** founded **2001:** developer of Li-thin-film battery cells. **2009:** developer of Li-thin-film battery cells, modules.	**2001:** RFID, smart cards, medical devices, microelectronics, consumer products, semi-conductors. **2010:** Energy Harvesting, Autonomous Wireless Sensors, Powered Cards, RFID, Medical Devices, Memory and RTC Backup Power, Military. **2012:** Energy Harvesting, Autonomous Wireless Sensors, Powered Cards, RFID, Medical Devices, Memory and RTC Backup Power, Military, Consumer Devices(smartphones and tablets).	**2008:** partnership-Lockheed Martin for defense and civil applications. **2010:** partnership-Distribution channels (Arrow Electronics, Tokyo Electron Device, KOGENT). **2010:** partnership-Texas Instruments (Digital Signal Processor Solution), MicroStrain (Wireless Sensor Network for Military Helicopters). **2012:** partnership-Alpha Micro (WIRELESS COMPONENTS).	**2013:** acquired by Apple
Amprius	**2008:** founded based on licensed patents from Stanford University. **2009:** developer nano-materials (silicon anode). **2010:** developer materials, cells. **2016:** partnership-Meyer Burger (Netherlands) B.V. to develop high-volume cell manufacturing.	**2010:** EVs, consumer electronics. **2016:** drones, wearables, EVs.	**2019:** partnership-Airbus Defense and Space (solar–electric, stratospheric Unmanned Aerial Vehicle (UAV). **2021:** partnership-US Army(drones).	**2023:** operating
Pellion Technologies	**2009**: founded based on licensed patents from MIT. **2011:** developer cathode material (Mg-ion). **2012:** developer material and cells by using advanced computer modeling.	**2012:** consumer electronics, EVs.	**-**	**2019:** out of business
QuantumScape Corporation	**2010:** founded based on research from Stanford University	**2020:** EVs	**2012:** partnership-Volkswagen (battery cell development and	**2020:** IPO via SPAC

	2013: Filed a patent for a solid-state energy storage systems and devices. **2020:** developer of solid-state Li-metal batteries – anode-less cell design.		testing for electric vehicles). **2018:** joint production project with Volkswagen for mass production of solid-state batteries.	
Sila Nanotechnologies	**2011:** founded based on self-research in collaboration with Georgia Tech. **2013:** developer of silicon-based anode. **2013:** developer of composites for cathode (lithium disulfide (Li_2S))	**2013:** consumer electronics, EVs, energy storage. **2018:** consumer electronics, EVs, electric power grid, electrified flight.	**2018:** partnership-BMW to develop silicon anode material for the automotive market. **2019:** partnership-Daimler. **2021:** partnership-Whoop fitness wearable.	**2023:** operating

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