Technological Development Trajectories of the Component Technologies in Battery Electric Vehicles

by

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ABSTRACT

As the concern about climate change grows, interest in battery electric vehicles (BEVs) is rising. BEVs are forecasted to constitute about 40% of passenger vehicle sales in 2035. While BEVs produce no emissions from the tailpipe, they face challenges, such as driving range and refueling time, that require technological advancements to improve performance and social acceptance. Since the evolution and replacement of component technologies have propelled the BEV progress, mapping their development trajectories may yield insights into future evolutions.

This thesis explores the technological development trajectories of batteries, ultra capacitors, battery management systems, electric motors, power electronics, and heat pumps, using main path analysis with U.S. patents published up to 2023. This analysis method can detect technological development trajectories and key patents in the trajectories by identifying the patents frequently cited, taking advantage of enormous patent data.

The results reveal that critical innovations do not necessarily occur when many innovations occur. Regarding some technological categories in some technology fields, such as battery circuit arrangements of power electronics, important innovations have been made constantly, and the trends are suggested to continue. On the other hand, other technical categories, such as magnetic circuits of electric motors, are critically innovated recently and intensively along with the increase in attention due to their high potential to improve performance. In addition, obtaining U.S. patents for core technologies, including batteries, battery management systems, electric motors, power electronics, and heat pumps, is crucial to gaining U.S. BEV market share, though it is not the case to succeed in the global market. Furthermore, their patents are not necessarily critical innovations in the technological development of the field. Current trends illustrate that significant BEV innovations are distributed across various entities. This suggests that though patents in the automotive industry have been typically held on verticals, diverse supply chain strategies, including incorporating innovative startups into their own companies or entering into horizontal partnerships with companies that have emerging technologies, are gaining importance in staying competitive in a market where leadership in each technology can swiftly change.

Thesis supervisor: Dr. Bruce G. Cameron
Title: Director, System Architecture Group

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List of Acronyms

AC	alternating current
BEV	battery electric vehicle
COM	Classification Overlap Method
CPC	Cooperative Patent Classification
DC	direct current
DSM	design structure matrix
EV	electric vehicle
FCEV	fuel cell electric vehicle
GaN	gallium nitride
GBFP	genetic backward-forward path analysis
GKPM	Genetic Knowledge Persistence Measurement
GP	global persistence
HEV	hybrid electric vehicle
HVAC	heating, ventilation, and air conditioning
HPP	high persistence patent
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
IPC	International Patent Classification
LP	layer persistence
LPP	low persistence patent
MOSFET	metal-oxide-semiconductor field-effect transistor
Na/NiCl2	Sodium-nickel chloride
Ni-Cd	nickel-cadmium
Ni-Fe	nickel-iron
Ni-MH	nickel-metal hydride
Ni-Zn	nickel-zinc
SiC	silicon carbide
Si-IGBT	silicon-insulated-gate bipolar transistor
UPC	United States Patent Classification
USPTO	United States Patent and Trademark Office

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Chapter 1

Introduction

1.1 Motivation

As the concern about climate change is growing, the global trend towards low or zero-emission vehicles is accelerating. Annual sales of light-duty electric vehicles (EVs) worldwide rose from under 10,000 units in 2010 to over 6.5 million globally by 2021. Out of these EV sales, battery electric vehicles (BEVs), which are exclusively powered by a battery bank, account for approximately 70% [1]. BEVs are forecasted to constitute 38.7% of passenger vehicle sales in the year 2035 [2]. They are highly efficient and produce no emissions from the tailpipe, while they have good acceleration [3]. However, some BEV performance aspects, such as driving range and refueling time, as well as BEV purchase price, have challenges [4]. These performance drawbacks and the high cost of BEVs can potentially be solved by improving related technologies, and therefore, the prosperity of BEVs that are consumer-acceptable and business-profitable hinges greatly on technological innovation in the BEV field [5]. While many technologies make up a BEV, not all of them are increasing performance at the same rate: some technologies, such as lead acid batteries, are stagnant, while other technologies, such as charging and power electronics, are rapidly progressing [5], and translating into increased driving range. Manufacturers must make bets on technologies to integrate because they cannot invest in all BEV technologies at once. Hence, uncovering the technological evolution paths of BEV component technologies would inform decisions about what technologies to include today in BEVs because they will continue to grow and what technologies are not yet ready but are likely to mature within the next 5 years and are worth planning around.

1.2 Background

The idea of EVs has a long history. In the early nineteenth century, an electric motor that consumed electricity as a means of transportation was developed, but a key requirement to produce EVs was the development of rechargeable batteries. In the late nineteenth century, EVs that had rechargeable batteries were delivered [6]. The modern era of EVs can be traced back to the 1970s, marked by a surge in oil prices, which prompted efforts to cut down on fuel derived from oil. This period also saw environmental advocates championing the cause of EVs. A significant revival in the marketing of EVs occurred in the mid-1990s, starting electric car production on a mass scale [7].

The key architectural decision for BEVs is that an electric motor powered by batteries takes the place of the internal combustion engine (ICE) and fuel tank and that the vehicle is connected to a charging station when not in use [3]. BEVs have many advantages. They produce no emissions from the tailpipe. The power train architecture is simpler than ICEs, and they have good acceleration [3] [8].

However, despite these benefits, BEVs also encounter considerable obstacles, and the improvement of societal acceptance of BEVs is essential for their widespread market penetration. Range anxiety, which comes from a shorter range than traditional vehicles and time-consuming charging processes, emerges as a critical obstacle for consumers. The initial high cost of purchase also acts as a deterrent for potential buyers [3] [8] [4].

Technological improvement of the component technologies of BEVs has fostered their development and market adoption. Batteries, which serve as the energy storage system in BEVs, are a critical technology. The primary metrics for comparing batteries are energy density, power density, cycle life, calendar life, and the cost per kWh. For example, lead acid batteries feature low specific energy and have brief cycle and calendar lifespans, but their affordability renders them suitable for BEVs with a small range. Conversely, lithium-ion batteries, considered the most promising for the near future due to their high energy density, efficiency, and long lifespan, are at a high cost, and a variety of lithium-ion batteries have been developed [3] [4]. Supercapacitors, or ultracapacitors, have been evolving in the last few decades. They boast a higher power density and an extended life cycle yet possess a lower energy density compared to batteries, which suggests pairing supercapacitors with batteries might hold significant promise [3]. However, batteries are not the only input technology: electric motors are still improving performance and may also contribute to increased range in the future. Electric motors, which replace internal combustion engines of traditional internal combustion engine vehicles (ICEVs), vary their efficiency with torque and speed. DC motors were once viewed as the optimal technology for BEVs due to the simple control and low cost, but the requirement of regular maintenance renders the technology inappropriate for the broad-scale adoption of BEVs. Instead, some types of AC motors are typically considered for BEV use [3].

1.3 Objectives

As shown in the history of BEVs, the evolution and replacement of component technologies have propelled the progress of BEVs. Mapping out the technological advancement trajectories of each technology could reveal the historical technology trends, including the focused technology and key innovation players, and offer suggestions for forthcoming technological development directions. When the mapping is integrated with supplementary data, including market and industry trends, it may yield additional insights into prospective innovation strategies. This thesis aims to shed light on them by addressing the following essential questions.

1. What is the historical technological improvement trajectory for each component technology of BEVs followed in development? How were technological clusters developed in the trajectory? Which topics and patent holders played important roles in the improvement over time? How were the patent trajectories related to the actual events?
2. Based on the trajectories detected in Question 1, what can be said about the future potential topics of each component technology? Which technologies would have more potential as substitutes? What kind of events may trigger such a replacement? Referencing the trajectories with EV markets and industry trends, what can be suggested as hopeful strategies for the amplification of the technologies?

This thesis takes advantage of the enormous amount of patent data and structured information originally published by the United States Patent and Trademark Office (USPTO), which was used as empirical data to identify the technological trajectories in the previous research [9] [5].

1.4 Outline

This thesis is structured as follows to facilitate the investigation of the research questions in Section 1.3.

- **Literature Review**: Chapter 2 provides an overview of the current BEV landscape relevant to this thesis. It begins with context around the component technologies and challenges of BEVs. It then describes the previous methods to analyze technology infusion, following zooming in directly to patent-based analyses of technological improvement. It also discusses past failures to infuse technologies and the reasons for failure.

- **Data and Method**: Chapter 3 begins by describing the data used in this study to explore the technological development of BEV component technologies. It then frames the methods used for the analysis, including how and when patents are clustered by patent type and how the paths are analyzed for distribution of patent ownership and patent owner motivation for patenting.

- **Results**: Chapter 4 reports the results of the analysis. It begins with the patents on the main paths of technological development trajectory in each technological domain/subdomain, then provides the images of the paths, and concludes with the clusters and trends of the detected patents.

- **Discussion**: Chapter 5 describes the insights gained from the analysis results through the lens of the research questions. Specifically, what architecture choices may represent bets on specific technologies improving over time, how different players might be willing to take different technology risks based on their market positions, and what automotive industry players could consider piloting as a means to explore forthcoming technologies despite their lack of commercial viability today are examined.

- **Conclusions**: Chapter 6 provides the conclusions of this study. It also lays out recommendations for future studies in this field.

Chapter 2

Literature Review

Context around three key concepts is important background information to understand for this thesis. These include key technologies of BEVs and their challenges, the concept of technology infusion and previous methods to analyze technology infusion, and BEV development analysis using patent data. This chapter provides the context for each concept and helps bring the reader up to speed on the research landscape relevant to the analysis of this thesis.

2.1 Key technologies of BEVs and their challenges

BEVs are 100% all-electric vehicles that totally run on the power put away in the batteries introduced in vehicles [6]. The typical power train architecture is shown in Figure 2.1 [6] [8] [10].

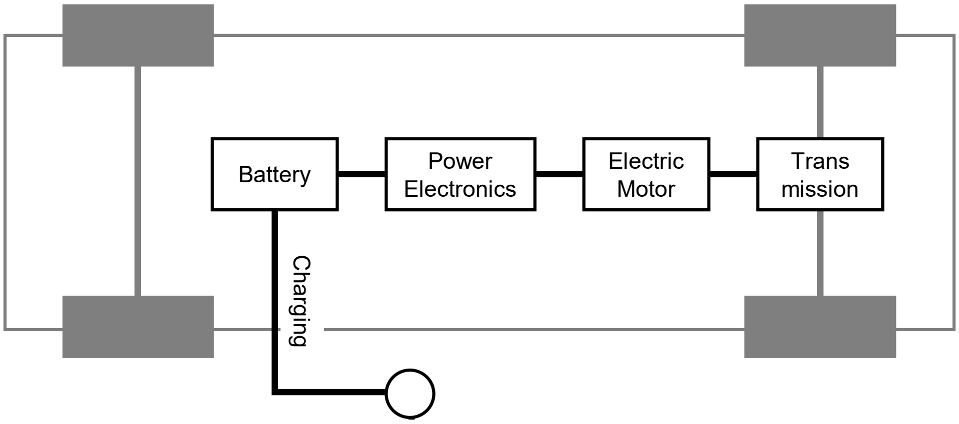

Figure 2.1: Typical power train architecture of BEVs.

One of the key components of a typical BEV is a traction battery pack at high voltage, which stores power to provide to an electric motor. A BEV also has a small auxiliary battery at low voltage, which is used for lighting, low-power applications, and control systems, connected to the traction battery through a DC/DC converter

[11]. However, batteries of a BEV usually refer to the traction battery pack, and in this paper, the batteries related to a traction battery pack are referred to as simply batteries. The battery management system is also a crucial technology of a BEV battery system to safeguard the batteries from harm, enhance and forecast battery lifespan, and keep the battery operating accurately and reliably [11].

A BEV has a charging port to communicate with an external power supply to charge the batteries. An onboard charger is also necessary to extract the AC power supply from the household or any other power source and convert it into a DC supply to charge the battery [6].

Another essential part of a BEV is an electric motor, which draws power from the batteries to turn the wheels and enable the vehicle to move. Power electronics, which is also a core technology, helps convey the power supply from the battery and the speed and torque control. There is a transmission between the electric motor and wheels, which transmits the mechanical force in the same way it works between the internal combustion engine and wheels of an ICEV [6] [8].

Vehicles are equipped with thermal management systems to control temperature. While ICEVs can utilize the engine's waste heat for heating purposes, BEVs require alternative heating sources for cabin warmth due to the lack of engine waste heat. A heat pump system is a solution that enhances the driving range of a BEV in cold weather conditions [12].

In the following, an overview of major BEV-specific technologies is described.

2.1.1 Battery

The battery is the most fundamental and critical technology in any BEV. The performance and design of other parts and components in a BEV are significantly influenced by the characteristics and parameters of its batteries [6].

A battery pack in a BEV comprises numerous battery cells organized into strings and modules. A battery cell is the smallest unit within a battery pack. When individual cells are grouped or arranged together, they form a module. When the modules are assembled and arranged in a specific configuration, they create a battery pack. The modularity level can vary depending on the specifications. The number of cells arranged in series sets the overall voltage of the battery pack. To enhance the capacity, the strings must be connected in parallel and evenly. The electrochemical battery cells convert chemical energy into electrical energy. Each cell includes a positive electrode, cathode, and a negative electrode, anode, both of which are immersed in an electrolyte. The chemical reaction between the electrolyte and the electrodes generates electricity. The materials and types used for the electrodes and electrolytes significantly influence the specifications of the batteries [6].

The primary metrics for comparing batteries are energy density, power density, cycle life, calendar life, and cost per kWh. Additionally, volume and safety are considered, with energy efficiency and self-discharge being secondary considerations. Batteries are designed based on a balance between energy and power densities. For BEVs, batteries are typically sized based on the energy needed to achieve a desired range. The relationship between driving range and battery capacity is not straightforward because the added weight of the battery decreases road efficiency. This highlights the importance of comparing batteries based on their energy and power densities. The cost of the battery constitutes a significant portion of the total BEV cost, making cost reduction vital. The cycle and calendar lives of a battery, which greatly depend on usage, are also crucial because if these are shorter than the lifespan of the BEV, leading to battery replacements, the overall cost of ownership for the BEV significantly increases [3].

Lead acid battery

The first type of battery technology employed in transportation was the lead-acid battery [10]. This is one of the most established batteries utilized in BEVs.
It features a positive electrode made of lead oxide and a negative electrode made of lead, both immersed in a sulfuric acid electrolyte. During discharge, the lead at the negative electrode and the lead oxide at the positive electrode react with sulfuric acid, resulting in the formation of lead sulfate and the conversion of the electrolyte into water. This chemical reaction releases energy, and when energy is supplied, the reaction reverses [6].

Lead acid batteries are relatively inexpensive, costing around USD 100/kWh. However, they have a low energy density, typically between 20 and 40 Wh/kg, and are heavy.[3]. Their power density is also relatively low at about 240 W/kg [6]. Compared to other major battery technologies, both the cycle and calendar life are short [3]. Maintenance involves regular inspection of electrolyte levels, and this battery technology is not considered environmentally friendly [10]. Additionally, the technology is mature, with limited potential for further improvement. Due to these factors, while lead-acid batteries are suitable for low-performance, small-range neighborhood vehicles, they are generally not considered for use in future BEVs [3] [10].

Nickel battery

Lead acid batteries were superseded by nickel batteries, which are considered relatively mature technologies with higher energy densities. Many commercial BEVs adopted nickel batteries; however, they exhibit several drawbacks, such as poor charge and discharge efficiency and a high self-discharge rate [10].

Nickel batteries use nickel in the positive electrode and come in various types, each with unique characteristics. Among these, nickel-zinc (Ni-Zn) and nickel-iron (Ni-Fe) batteries have been deemed unsuitable for BEVs due to their limited lifespan and lower energy density [6]. Nickel-cadmium (Ni-Cd) batteries suffer from a memory effect, which requires high charge and discharge rates and are not suitable for BEVs. They have been phased out due to the toxicity of their components [10].

Nickel-metal hydride (Ni-MH) batteries involve a reaction between metal hydride and nickel oxyhydroxide, producing nickel hydroxide and metal. This technology is mature but is considered to have reached its developmental peak in terms of cost reduction and performance. Ni-MH batteries are priced around USD 700–800/kWh and boast a high power density of up to 2000W/kg. However, with an energy density of 45 to 80 Wh/kg and poor charge, it is considered insufficient for the needs of BEVs [3] [6]. Additionally, the poor charging efficiency and the extremely high self-discharge rate, which can reach up to 20% per month, have restricted the use of Ni-MH batteries in future BEVs [10].

Sodium-nickel chloride (Na/NiCl2, Zebra) batteries were introduced into the vehicles at about the same time as Ni-MH batteries [10]. These batteries offer several advantages, including safety, low cost - approximately one-third the price of Lithium-ion batteries - a long cycle life superior to 1000 cycles, and the ability to be nearly fully discharged without impacting lifespan. With an energy density of about 120 Wh/kg, they are more promising, though their power density of 150W/kg is low for exclusive use in BEVs and may need to be paired with other power sources like supercapacitors [3]. Additionally, Zebra batteries use sodium salt as the electrolyte and operate at extremely high temperatures, ranging from 245 to 350 degrees Celsius, which presents significant challenges for thermal management and raises safety concerns [10].

Lithium-ion battery

Lithium-ion batteries are the most reliable and dominant technology in the recent battery market for BEVs. Their development has been steadily increasing over the last several years [6].

They have high energy density since lithium has the highest electrochemical potential and a low equivalent mass [3]. The energy density varies from 60 to 250 Wh/kg, while the power density can reach up to 2000 W/kg [6]. They are highly efficient and have a long lifespan, with significant potential for further improvements. However, they are costly, with prices exceeding USD 700/kWh. Safety issues also arise, as overcharging can lead to fires and destruction. Additionally, there are concerns about the availability of necessary materials. Lithium-ion batteries come in a wide range of chemistries, each with its own set of characteristics and varying degrees of development [3].

Solid-state battery

Solid-state batteries are considered a practical alternative to lithium-ion batteries [13]. Currently, the only solid-state batteries widely available on the market are polymer solid-state batteries used in some buses, and it is expected that the capacity of solid-state batteries will substantially rise between 2025 and 2030 with the introduction of other types of solid-state batteries [14]. Several leading mobility companies have recently shown significant interest in solid-state battery technology [15]. Solid-state batteries use solid electrolytes that also serve as separators, unlike current batteries that use rechargeable liquid electrolytes [13].

Safety is significantly enhanced with solid electrolytes, which allows for an increase in energy density [15]. Energy density for emerging solid-state batteries is estimated up to 350 to 500 Wh/kg with different solid electrolytes and lithium anodes [14]. Solid electrolytes are more energy-dense, enabling faster charging, greater range, and longer battery life. Solid-state batteries also perform better under extreme temperatures, both hot and cold. As a result, solid-state batteries are more stable and perform better [13]. However, Solid-state batteries face certain challenges, including reduced ionic conductivity in the solid electrolytes. Selecting the right solid electrolytes is complex, as it requires balancing multiple factors such as conductivity, compatibility, stability, cost, environmental impact, and electrochemical performance. Solid electrolytes are classified into three main types: inorganic, polymeric, and composite materials. The properties of these materials significantly influence the manufacturing processes of solid-state batteries [15].

2.1.2 Ultra capacitor

Ultra capacitors, also known as supercapacitors, differ from batteries but can be part of an energy storage system of BEVs. Unlike batteries that store energy through chemical reactions, ultra capacitors store energy physically [16].

Ultra capacitors are made with porous carbon electrodes, which offer a large surface area of 1000 m^2/g with the electrolyte to store energy electro. This high capacitance of ultra capacitors has been developed through improved nanotechnology. The high energy efficiency exceeding 90% is also the advantage of ultra capacitors [8]. In addition, they have a high specific power of up to 5000 W/kg, which enables them to be charged and discharged much faster than batteries [16]. This is crucial to overcome the challenge of charging time. Ultra capacitors also have a long cycle life of over 300,000 cycles [16]. Despite having these advantages, ultra capacitors are low in energy density of 5-15 Wh/kg, which means they cannot replace batteries as the sole energy storage solution in BEVs [8].

2.1.3 Battery management system

A battery management system performs two primary functions. Firstly, it monitors the battery's condition, including its State of Charge, State of Health, and Remaining Useful Life. These metrics are essential for optimizing charging and discharging processes. Secondly, the battery management system ensures that the battery operates safely, efficiently, and without causing damage. Since battery cells, arranged in both parallel and series formations, can have slight variations in characteristics, it is critical to minimize differences in charging levels among the cells to enhance runtime per cycle, prevent damage, and extend the overall life of the battery stack [3] [11].

Advancements in battery management system technologies of monitoring and operations, such as measurement and algorithms, are believed to greatly enhance the efficiency of BEVs and prolong their battery life. These improvements are vital for increasing both the range and the lifecycle cost of BEVs, potentially overcoming current challenges in social acceptance [3] [11].

2.1.4 Charging

The battery pack in a BEV is charged externally from the power grid using a charger. A charger is necessary because the power grid delivers electricity in alternating current (AC) form while the battery operates on direct current (DC). To bridge this gap, the charger converts AC from the grid to the appropriate DC level needed for charging the batteries, functioning primarily as an AC/DC converter or rectifier. For fast charging stations, an additional DC/DC converter is sometimes incorporated into the charger to enhance energy conversion efficiency. Chargers can be installed either onboard or offboard a vehicle. Onboard chargers are typically smaller and lighter to minimize the weight impact on BEVs, and they are generally used for slower charging due to their lower power rating. Conversely, offboard chargers are stationed at specific locations to facilitate fast charging services [10].

Various technical solutions for charging electric vehicles have been developed. The most common and favored solution is a conductive charge, which is efficient, compact, and lightweight and allows bi-directional power flows. The charging is arranged into three levels. Level 1 uses 120V in the US, with which home outlets can be used though charging is slow, Level 2 uses 240V, with which faster charging beneficial for daily work commute is possible though charging station and electrical wiring for higher voltage power is necessary, and Level 3, or Fast Charging, uses 480V, with which charging 80% in 30 minutes to one hour could be possible though facilities are costly diverse attachment types, such as CHAdeMO, SAE, and CSS, confusing to potential purchasers and charging station administrators [6] [3] [10]. Battery switching stations, where a battery pack is replaced by an already fully charged one, and inductive chargers, which use magnetic induction between specifically designed transformers to transmit energy, are also charging solution technologies. The development of charging infrastructure is vital for public adoption of BEVs, as it can help reduce range anxiety through a suitable charging station network [3].

2.1.5 Electric motor

An electric motor, which provides the tractive effort to drive the wheels, is a critical part of the BEV propulsion system, converting electrical energy into mechanical energy. The electric motor needs to be high-performing, energy-efficient, lightweight, and durable enough to handle frequent starting and stopping cycles. [8].

Electric motors have advantages over internal combustion engines. The conversion efficiency of electric motors is impressively high, ranging between 70% and 95%. They boast high torque and power density, along with superior torque characteristics at low speeds. Electric motors can also function as generators during braking to recuperate energy. Drivers value their quiet operation and the rapid, smooth acceleration they provide. Moreover, electric motors are robust, reliable, and reasonably priced, resulting in an attractive choice for vehicle propulsion. Various types of electric motors exist. It is crucial to choose an electric motor that is highly adaptable to a range of working conditions and adverse environments and capable of managing rapid changes in motion during both acceleration and deceleration [3].

DC Motor

DC motors were once regarded as the most suitable propulsion technology for BEVs due to their simplicity and low cost, stemming from straightforward control electronics and high starting torque. However, they require regular maintenance because they use commutators and brushes that are in constant contact and prone to wear. The losses caused by the windage and friction in the rotor region are key losses that vary with rotational speeds and require complex cooling systems. Therefore, though many BEVs with a DC motor are available in the market, DC motors are less suitable for widespread adoption in BEVs, and AC motors are getting more popular, especially in high-power applications [3] [8].

An AC motor by itself is generally less expensive than a DC motor. However, it necessitates complex and expensive power electronics, including a DC/AC inverter, making the total cost of an AC motor system higher. The benefits are a higher power density, which is crucial for the use of smaller, lighter motors, and greater efficiency, which extends the driving range for a given battery capacity. For BEV applications, three main types of AC motors are commonly used: induction motors, permanent magnet motors, and switch reluctance motors [3].

Induction motor

An induction motor, also known as an asynchronous motor, generates torque through the electromagnetic interaction between the magnetic field of the stator windings and the induced field in the rotor.

An induction motor has advantages in cost, reliability, technological maturity, robustness, and lifetime compared to other major electric motors, whereas other performance indices are moderate [3] [8]. Power losses in induction motors stem from copper-iron losses in both the stator and rotor, in addition to friction and windage. A cage/slip-ring induction motor is seen as a viable option for high-power electric propulsion systems due to its inherent power density, higher efficiency, and low maintenance requirements. Additionally, its simple and robust structural design allows it to produce high torque, making it suitable for a BEV [8].

Permanent magnet motor

With the improvement of permanent magnet materials, a permanent magnet motor has become attractive. Permanent magnet motors offer high efficiency. Besides, it has a high energy density because of its hardshell rotor construction [3] [8].

A permanent magnet motor is suitable for very high-speed applications. It is currently seen as the best technology for small and moderate power needs, between 25 and 150 kW, which corresponds to the need for a passenger car. However, its cost remains high due to the permanent magnetic materials [3] [8].

Switch reluctance motor

A switched reluctance motor is characterized by its simple salient-type structure, featuring concentric windings on the stator but no windings on the rotor [3].

This motor is regarded as an upcoming technology with high potential due to its straightforward construction and low manufacturing costs. Its robust design allows it to operate effectively over a wide range of speeds and withstand high temperatures. Additionally, it exhibits a lower rate of idle losses and is durable enough to function in challenging operational environments [3] [8].

Despite these advantages, the motor presents challenges in terms of control and design. It experiences significant torque ripples caused by changing inductance, even at lower speeds, and issues with acoustic noise, both of which are areas that still require resolution [3] [8].

Even if electric motors are well established, applying them in automotive powertrains introduces new challenges related to weight, robustness, and reliability. Potential future enhancements for electric motors might include lowering the cost of high-temperature permanent magnets, developing controllers for safer operation of subsystems, and reducing the number of sensors required in the motor [3].

2.1.6 Power electronics

Power electronics in a BEV manage the electric motor and oversee the detection of failures within the propulsion system, including components like bearings, rotors, and stators [8]. Power electronics comprise various converter and inverter topologies, which involve selecting suitable power-switching devices and switching schemes. Proper control and monitoring systems are also implemented in the power electronics to facilitate the maneuvering of BEVs. The main requirements for power electronics are high efficiency, small size, and low cost [8]. They account for a significant portion of the total cost of BEVs, presenting a substantial opportunity for cost reduction [3].

In early generations, metal-oxide-semiconductor field-effect transistors (MOSFETs) were the preferred switching devices, later replaced by silicon-insulated-gate bipolar transistor (Si-IGBT) modules. With technological advancements and improvements in silicon carbide (SiC) and gallium nitride (GaN) devices, newer and more efficient topologies have developed [8]. Despite these advancements, there are still many areas requiring improvement. Components such as diodes and switches need to withstand high temperatures and significant levels of vibration. Capacitors require enhancements, and further research into dielectric materials is necessary. Inverters should be simplified and ideally incorporate electromagnetic interference filters while also being fault tolerant. The primary challenge remains in developing higher heat resistance or better cooling systems and reducing the volume of the devices to make them more suitable for BEVs [3] [17].

2.1.7 Heat pump

A heat pump is used as an efficient approach to operate the vehicle heating, ventilation, and air conditioning system (HVAC) of a BEV. The HVAC system has the highest energy consumption among all accessory loads in a BEV, potentially using a significant portion of the total energy stored. This significantly impacts the reduction in driving range, and therefore, maximizing the efficiency of thermal control systems to reduce energy consumption in both cooling and heating modes is crucial [18].

While ICEVs can utilize the waste heat from the engine for heating purposes, BEVs require alternative heating sources due to the lack of engine waste heat. A heat pump captures heat from the ambient air and delivers the heat to the cabin through the use of heat exchangers and a compressor [12]. Because of the energy efficiency of heat pumps, heat pump systems have been stepping into the market of BEVs. A heat pump system is expected as a solution that enhances the driving range of a BEV [18].

In this section, the literature reviews of the major component technologies of BEVs that differ from those of ICEVs have been conducted. In this thesis, I choose the battery, ultra capacitor, battery management system, electric motor, power electronics, and heat pump as the target for analysis, excluding charging, whose development is greatly influenced by the infrastructure spending available and infrastructure penetration.

2.2 Technology infusion

Technology infusion can be defined as substitution or adding technology into an existing system to evolve the system. For a smooth technology infusion, it is important that the technology aligns with the requirements of the existing system or that the system is initially designed to accommodate future technological updates [19] [20].

Technology infusion is being carried out regularly in various fields, though research continues to explore a quantitative analysis of what drives the success or failure of new technologies in the marketplace. Most new technologies realize their value when integrated into a parent system [21]. To give an example of designing a system flexible to future options, when a bridge over the Tagus River in Lisbon, Portugal, was constructed, it was designed robustly enough to support trains, though it was not required initially to provide future options for the public authorities and metropolitan rail line across the river was created many years later. To give another instance, a modular system design grants system creators and operators the right to replace components, such as computers, to be upgraded to newer models with flexibility, unlike when a system is completely integrated without flexibility [22].

Development is only achievable by accepting uncertainty [23]. Real option analysis is a method to deal with uncertainty in system design as valuable options. Flexibility higher than the norm is introduced into the design of systems to make it possible for options to be exploited at the correct time according to the justified value of the options based on the option analysis [22]. Smaling & de Weck (2007) developed a technology infusion assessment methodology to quantify the potential performance value of new technologies using multiobjective Pareto analysis. They measured the cost of introducing a new technology by quantifying the amount of design change using the component-based design structure matrix (DSM), which shows the interconnections of components in a system, of the original system and the system with the technology, and they quantified risks and opportunities based on the benefits and costs of infusing the technology [21]. Furthermore, built on this methodology, Suh, Frust, Mihalyov & de Weck (2010) quantified the change in the net present value of introducing a new technology [24]. Kellari (2016) used a method of developing a framework to quantify aircraft architecture and introducing a metric for measuring its performance, which allowed for predicting major drivers for performance improvement by quantifying the performance achievable with different technological options [25].

To assess the technology infusion with these methods to take advantage of a new or substitute technology, it is important to predict the potential component technologies that may be infused in a specific system.

2.3 BEV development analysis with patents

Previous researchers have used patents to study EV development as a repository of technological inventions [5]. Businesses protect their innovations by using both patents and trade secrets [26]. While patents are published and can be enforced against infringers, trade secrets are maintained as secrets and are challenging to enforce. Therefore, patents and trade secrets cannot be applied to a single innovation simultaneously, and not all innovations are published as patents. However, patent data is useful in understanding technology development, while empirical data is not easy to collect and sometimes may not be reported due to confidentiality and other concerns [5].

Some studies compared the technology development between traditional power source vehicles and alternative energy vehicles using patents. Sick, Nienaber, Liesenkötter, Stein, Schewe & Leker (2016) discussed whether a sailing ship effect, which is that technological competition between the established technology and the newly emerged technology pushes the innovation of the established technology, exists in the automotive industry by comparing the patent data of ICEVs with different types of EVs. They concluded that the major part of the innovation behavior is subject to the sailing ship effect, and automotive industry players should consider the effect in strategic technology planning [27]. Borgstedt, Neyer & Schewe (2017) compared the patent holders of powertrain technologies by type of automobile to analyze automotive supply networks [28]. Yuan & Cai (2021) forecasted the future development of drivetrain technologies for automobiles, including EVs, on the basis of the patent growth curve and ranks led by entropy. They suggested that hybrid electric vehicles (HEVs) show the most potential for growth, followed by BEVs and ICEVs, while fuel cell electric vehicles (FCEVs) are advancing at a slower pace [29].

Some researchers have investigated the broad evolutionary trends in electric vehicle innovation with patents. Zhang, Guo, Wang, Zhu & Porter (2013) created a global technology roadmap for EVs to illustrate the development of the technologies from 1985 to 2010 using a model they constructed for technology roadmapping. The roadmap displayed the following: The initial phase surrounding materials occurred around 1990. Around 1995, the focus shifted to mechanism dynamics techniques, marking a starting point for EV development. In 1997, advancements in battery technology began and became crucial for future research and development. Lastly, breakthroughs in hybrid power started around 2002 [30]. Sun, Geng, Hu, Shi & Xu (2018) examined the evolution of EV patents in China, focusing on the dimensions of patent numbers, technological innovation classifications, and the geological distribution of patents, using a social network analysis approach that analyzes the structure of social actors, including individuals and organizations [31]. Yuan & Li (2021) utilized priority patent applications and international patent families to chart the transnational diffusion of BEV technology from a global technology innovation standpoint [32]. Ma, Xu & Fan (2022) analyzed the patents from 1970 to 2016 related to EVs using the information technologies of text mining, clustering, and social network analysis to grasp the characteristics and trends of EV technology developments. They found that the key topic in EV technology is developing ways to charge batteries safely and quickly at a charging facility and distributing the energy to each storage and that wireless charging technology is at the forefront of EV research. They also revealed the following from the analysis of patent holders: technical collaborations and knowledge sharing are mostly confined within a country due to geographical and national factors; component manufacturers hold numerous EV patents, reflecting a shift of innovation pressure from car manufacturers to the supply chain; the EV battery sector faces intense competition and cooperates among companies.[33].

Other studies focused on a specific technological field related to EVs. Golembiewski, Stein, Sick & Wiemhöfer (2015) explored trends in battery technologies with regard to EVs by analyzing the categories and countries of the patent assignees within the battery value chain [34]. Aaldering, Leker & Song (2019) analyzed patents related to alternative powertrains to identify technology interaction relationships among patent classifications using social network analysis [35]. Lee (2020) analyzes the effects of artificial intelligence on EV technology innovation by using a machine learning-based method [36].

Feng & Magee (2020) broke down the EV-related technologies into the battery, charging and discharging, electric motor, and power electronics domains and further detailed these domains into subdomains: the lead-acid battery, nickel battery, and lithium-ion battery subdomains in the battery domain, the charging and discharging subdomains in the charging and discharging domain, the induction motor and permanent magnet motor subdomains in the electric motor domains, and the power electronics-hybrid and power electronics-other subdomains in the power electronics domain, to offer both a wider and more in-depth view of technology development. They examined 1) the technology performance improvement rate based on Moore's law of each domain and subdomain, 2) technology development trajectories using main path analysis of the power electronics-hybrid, lithium-ion battery, permanent magnet motor, and discharging subdomains, and 3) major patent assignees of the same four subdomains, using patent data until the first half of 2015 [5].

They concluded:

1) The estimated technology performance improvement rate suggests that batteries and electric motors have a slower improvement rate compared to charging systems and power electronics, and the slower progression could impede the widespread adoption of electric vehicles.
2) The main path analysis reveals the focus on subdomains, including the positive electrode in lithium-ion batteries and the rotor in permanent magnet motors. The identified current and emerging trends are the detailed switching technologies in power electronics for hybrid EVs, which might still be a focus in the future, and the silicon negative electrode in lithium-ion batteries, which is to be an emerging research trend in recent years. These insights help researchers and scientists identify and pursue hot and emerging research topics.
3) Since the players identified by the main path method in the EV industry are also significant market players, other market participants should monitor these companies' business strategies, develop crucial EV-related technologies, and seek partnerships with these players to stay competitive in the market [5].

Regarding the main path analysis, which is employed by Feng & Magee (2020), as mentioned in the previous two paragraphs, the background of this method is below. Technology trajectories provide a theoretical framework for understanding the evolution of technology [37] [38] [39]. Main path analysis, utilizing patent citation networks, is increasingly recognized as a common method for empirically determining technology trajectories. It was first introduced by Hummon & Dereian (1989) to map out the knowledge trajectory in the DNA field using the article citation network [40]. Subsequently, this method and its adaptations based on the patent citation network were applied to explore technology trajectories across various fields [41] [42] [43]. Feng & Magee (2020) employed a main path analysis method proposed by Park & Magee (2017) [9]. This method is capable of detecting simple and non-singular paths, as well as highlighting key patents in the trajectories, and it has also been successfully applied across multiple technological fields [44] [45] [46] [47].

This thesis aims to detect the historical technological improvement trajectories of BEV component technologies as well as the technological clusters and important players and make suggestions for the future development of the BEV field as described in the Introduction. Therefore, I applied the main path analysis method in this thesis. To analyze the technological categories that are major and relatively independent of external infrastructure, I choose the six domains - battery, ultra capacitor, battery management system, electric motor, power electronics, and heat pump, following the four battery subdomains - lead acid battery, nickel battery, lithium-ion battery, and solid-state battery, and four electric motor subdomains - DC motor, induction motor, permanent magnet motor, and switch reluctance motor.

The research gap between the previous paper by Feng & Magee (2020) [5] and this thesis is that 1) while they analyzed the patents published up to the first half of 2015, this thesis collected the patents until 2023 because covering the latest patents should be worth in the rapidly growing BEV field. Along this period selection, while Feng & Magee used COM based on the UPC and IPC systems to retrieve patent sets, this thesis applied a keyword-patent classification hybrid method based on the CPC system. These methodological details are described in Section 3.1. 2) In addition, while they analyzed the technology performance improvement rate, main paths, and major patent assignees, this thesis focused on the analysis of main paths and major patent assignees. 3) Another significant difference is the domains and subdomains. This thesis added the ultra capacitor, battery management system, and heat pump domains, the solid-state battery subdomain in the battery domain, and the DC motor and switch reluctance motor subdomains in the electric motor domain. Furthermore, Feng & Magee deepened into the main paths and patent assignees regarding the four subdomains: power electronics-hybrid, lithium-ion battery, permanent magnet motor, and discharging subdomains, which they detected as the subdomains with high improvement rates. Therefore, regarding the analysis of main paths and assignees, among the domains/subdomains, the lithium-ion battery and permanent magnet motor subdomains are targeted in common by them and this thesis.

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Chapter 3

Data and Methods

This chapter first describes the patent data and collection of patent sets used in this thesis to explore the technological development trajectories of each domain/subdomain that is decided to be analyzed in the Literature Review. It then frames the methods used to detect the main paths of each domain/subdomain: construction of patent citation network, measurement of knowledge persistence, and identification of main paths. Following these, the points of view for further analysis of the detected main paths are explained, including how and when patents are clustered by patent type and how the patent ownership is distributed. These steps are shown in Figure 3.1.

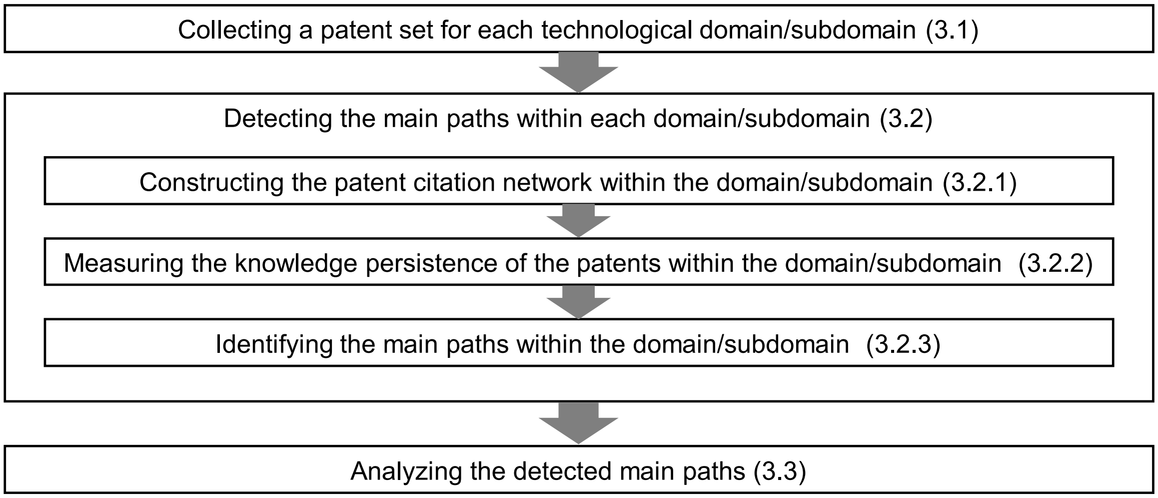

Figure 3.1: Steps in the methods.

3.1 Collection of patent sets

This thesis relies on U.S.-granted patents to explore the technological development trajectories of component technologies of VEBs. The sole use of U.S. patents is for two reasons. First, the U.S. patent system covers worldwide inventions.

Due to the large market size of the U.S. and its key role in technological innovation, most significant inventions registered with other patent offices are also filed with the USPTO [48], which ensures the inventions receive protection under U.S. law in the American market. Second, the U.S. patent system is the most representative compared to other relevant patent systems considering the amount and diversity of information [49]. The meticulous and thorough citation practices of the USPTO are crucial because the methods employed in this thesis depend on the citation networks of the patent sets. The patent sets are downloaded from the patent database provided by patsnap https://www.patsnap.com/.

Retrieving a patent data set representing each domain and subdomain is the basis of analyzing the technological development trajectory in this thesis. The Classification Overlap Method (COM), developed by Benson & Magee (2012 and 2015) [50] [51], has been applied in multiple studies to gather a relevant and relatively complete patent set for a specific domain [52] [53] [54] [5] [44] [45] [55] [56]. COM is a keyword-patent classification hybrid method. The patent sets using COM are retrieved based on both the United States Patent Classification (UPC) system and the International Patent Classification (IPC) system, selecting the overlapped patents from the representative UPC and IPC classes. However, the USPTO moved from using the UPC system to the Cooperative Patent Classification (CPC) system in 2013 [57], and the UPC system was discontinued after 2016 [47]. Therefore, COM is not applicable to establish patent sets after this year. Instead, a keyword-patent class method, a combination method of the keyword search and patent class selection based on the Cooperative Patent Classification (CPC), was employed by Campos, Henriques & Magee (2022) [47]. The CPC classes of the U.S. granted patents, including those granted before 2013, are published by the USPTO [58], and using the CPC system enables analysis of patents to date based on a consistent classification system. To overcome the weakness of using only the CPC classes and ensure that the most selected patents (~95%) were relevant, Campos, Henriques & Magee (2022) read the title, abstract, background of invention, and summary of invention of 300 patents within each patent set [47]. In this thesis, a keyword-patent classification hybrid method based on CPC is used for the following reasons. First, the CPC system has been used by many countries globally [57]. Second, given that the annual sales of BEVs have increased dramatically over the past decade, it is essential that the patent sets include patents published after 2016. This thesis does not adopt the procedure of reading 300 patents of each patent set due to the difficulty of judging the relevancy of each patent and targeting the wide component technologies of BEVs.

The specific CPC classes for each domain are selected as follows: First, a set of keywords related to the technology of the domain is searched in the patent database. Next, the CPC classes of some of the retrieved patents related to the technology are checked. Then, the definitions of the CPC classes [59] are examined to determine whether the classes are appropriate for the technology selections of the domain. Since the domains of battery, electric motor, and power electronics among the domains targeted in this thesis were analyzed by Feng & Magee [5], the CPC classes that are consistent with the IPC classes adopted by Feng & Magee are selected, referencing the concordances of the CPC classes and the IPC classes [60]. The specific CPC classes for each subdomain are selected with the same procedure, but also the classes are limited within the same class or sub classes under the classes selected for its parent domain.

The patent sets are retrieved from the patents with publication dates from January 1, 1976, to December 31, 2023. 1976 is when the United States Congress passed the Electric and Hybrid Vehicle Research, Development, and Demonstration Act, Public Law 94-413, under the occurrence of oil crises [61] [7]. The end time of 2023 is set because the latest yearly data available when the patent sets are extracted is the year. The search keywords and classes used to establish the representative patent sets are shown in Table 3.1.

Table 3.1: Patent set representative of each technological domain/subdomain.

Domain name		Patent search query			Number of patents
	Subdomain name	**Keywords**	**CPC classes**	**Publication date**	
Battery		“battery”	H01M	1976 - 2023	49,611
	Lead acid battery	“lead acid battery”	H01M4/14, H01M4/627, H01M4/68, H01M4/73, H01M4/82, H01M10/06, H01M10/121, H01M50/114, H01M50/541	1976 – 2023	620
	Nickel battery	“nickel battery”	H01M4/32, H01M4/52, H01M10/30	1976 – 2023	1,080
	Lithium-ion battery	“lithium ion battery”	H01M4/13, H01M10/052	1976 – 2023	5,050
	Solid-state battery	“solid state battery”	H01M6/18, H01M10/0562, H01M2300/0065	1976 – 2023	836
Ultra capacitor		“ultra capacitor” or “supercapacitor”	H01G, H01L29/00	1976 – 2023	512
Battery management system		“battery management system”	B60L, G01R, H01M, H02J	1976 – 2023	2,507
Electric motor		“electric motor”	H02K	1976 – 2023	9,111
	DC motor	“DC motor”	H02K	1976 – 2023	1,255
	Induction motor	“induction motor” or “asynchronous motor”	H02K17/00, H02K17/02, H02K17/04, H02K17/12,	1976 – 2023	287

			H02K17/16, H02K17/22, H02K17/26, H02K17/28, H02K17/30, H02K17/32, H02K17/34, H02K44/06, H02K49/02		
	Permanent magnet motor	“permanent magnet motor”	H02K1/17, H02K1/223, H02K1/27, H02K15/03	1976 – 2023	1,531
	Switch reluctance motor	“switch reluctance motor” or “switched reluctance motor”	H02K1/246, H02K19/06, H02K19/103	1976 – 2023	138
Power electronics		“power electronics”	B60L	1976 – 2023	1,039
Heat pump		“heat pump”	B60H	1976 – 2023	822

Patent sets in each domain aim to represent each technology, yet some patents overlap across multiple domains due to their applicability in various classes. Similarly, multiple subdomains within a domain can also share patents. Therefore, the patent sets of the domains or subdomains are not mutually exclusive, and those with significant overlap are likely to yield similar analytical outcomes [55]. Table 3.2 shows the percentage of overlapping patents between each pair of the six technological domains of BEVs, and Table 3.3 shows the overlapping percentage between the four technological subdomains in the battery domain and electric motor domain, respectively. Each block has a specific percentage that represents the overlap between the main domain/subdomain and other domains/subdomains. The values in the diagonal blocks indicate the percentage of unique patents in the focal domain. An obtained domain/subdomain with low overlapping is considered highly independent of the other domain/subdomain analyses [55]. Among the patent sets of six domains, the battery, electric motor, and heat pump domains exhibit over 90% unique patents. In contrast, the ultracapacitor, battery management system, and power electronics domains demonstrate 45-84% uniqueness, mainly due to overlaps with the battery domain. Especially, the battery management system domain overlaps 53% of the patents with the battery domain, which means the battery management system domain is heavily dependent on the battery domain. Within the battery domain, lead acid and lithium-ion battery subdomains possess over 93% unique patents, while nickel and solid-state battery subdomains show 78-84% uniqueness, overlapping with the lithium-ion subdomain. Each subdomain in the electric motor domain maintains about 90% unique patents.

Table 3.2: Percentage of overlapping patents between the six technological domains of BEVs.

BEV	Other domains						
Focal domain		Battery	Ultra capacitor	Battery management system	Electric motor	Power electronics	Heat pump
	Battery	96.7%	0.2%	2.7%	0.1%	0.3%	0.1%
	Ultra capacitor	15.8%	83.6%	0.6%	0	0	0

	Battery management system	52.7%	0.1%	44.8%	0.0%	1.6%	0.8%
	Electric motor	0.3%	0	0.0%	99.5%	0.2%	0.0%
	Power electronics	15.6%	0	3.8%	1.5%	78.5%	0.6%
	Heat pump	5.2%	0	2.6%	0.2%	0.7%	91.2%

Table 3.3: Percentage of overlapping patents between the four technological subdomains in the battery domain and electric motor domain.

Battery	Other subdomains				
		Lead acid battery	Nickel battery	Lithium-ion battery	Solid-state battery
Focal subdomain	Lead acid battery	98.4%	0.2%	1.5%	0
	Nickel battery	0.1%	83.6%	16.3%	0
	Lithium-ion battery	0.2%	3.5%	92.8%	3.6%
	Solid-state battery	0	0	21.7%	78.3%

Electric Motor		Other subdomains			
Focal subdomain		DC motor	Induction motor	Permanent magnet motor	Switch reluctance motor
	DC motor	90.8%	0.8%	7.8%	0.6%
	Induction motor	3.5%	92.7%	3.5%	0.3%
	Permanent magnet motor	6.4%	0.7%	92.6%	0.4%
	Switch reluctance motor	5.1%	0.7%	4.3%	89.9%

3.2 Detection of main paths

Main path analysis is employed to identify the technological development trajectory, enabling the extraction of developmental trends over time within a domain/subdomain. In this thesis, a main path analysis method named genetic backward-forward path analysis (GBFP), proposed by Park & Magee (2017) [9] is applied.

In this method, as the first step, a patent citation network within the domain/subdomain is constructed using citations between patents in the patent sets. Then, the knowledge persistence of each patent in the patent sets is measured, and the dominantly important patents in the domain/subdomain, high persistence patents (HPPs), are identified. Finally, the main paths among the HPPs are tracked.

This method has been applied in several technological domains [5] [47] [44] [45] [46]. MATLAB is used to compute in this main path analysis. The method steps are described in the subsequent sections.

3.2.1 Construction of patent citation network

A knowledge network for a technological domain/subdomain is constructed by using patent citations, under the premise that a patent citation indicates a transfer of knowledge from the cited patent to the citing patent. It focuses solely on knowledge transfers within the focused technological domain/subdomain, meaning only patent citations within the domain/subdomain are considered. Though there are many citations from outside the focused domain/subdomain, following the previous studies [9] [5] [47] [44] [45] [46], such citations are neglected because the purpose of this method is to detect the technology development trajectory within the domain. The pairs of cited and citing patents are obtained from the citation information of each patent downloaded from the database provided by patsnap.

3.2.2 Measurement of knowledge persistence

According to Martinelli & Nomaler (2014) [62], patents with high persistence represent crucial technological inventions within a technological domain. The idea of persistence is based on the concept that the influence of a patent on future technological advancements increases if the patent is frequently cited by subsequent descendent patents, thus ensuring its contribution persists in the technology [62]. Therefore, searches from the HPPs ensure that all essential knowledge is captured along the main paths. In addition, using both backward and forward searches makes it possible to uncover additional potential main paths that might be overlooked with only forward searching and to detect converging trajectories in technological developments [9].

In this thesis, knowledge persistence is calculated through the Genetic Knowledge Persistence Measurement (GKPM) developed by Martinelli & Nomaler (2014) [62]. The steps of GKPM are as follows.

First, the comprehensive lineage structure of the technological domain/subdomain is established by placing each patent into a layer. This step begins by identifying the *endpoints*, which are not cited by any patents within the domain/subdomain, and then assigning each patent to a layer in reverse order. The *startpoints*, which do not cite any patents within the domain/subdomain, are designated as the first layer, and then layer numbers for subsequent patents, including the *endpoints*, are determined. The number of the layer structure is determined by the length of the longest citation link sequences extending from the *endpoints* back to the *startpoints*. Each patent is placed into a single layer, even if the patent cites or is cited by two or more patents.

Second, on the basis of the layer-based citation network, the extent to which the knowledge of a patent is inherited by *endpoints* is quantified. The fraction of knowledge passed on from a patent to the subsequent layer is determined by dividing 1 by the number of backward citations the descendant patents receive. Consequently, the knowledge persistence of patent A is computed using the following equation:

$$KP_A = \sum_{i=1}^{n} \sum_{j=1}^{m_i} \prod_{k=1}^{l_j-1} \frac{1}{BWDCit(P_{ijk})} \tag{3.1}$$

where KP_A is the knowledge persistence value of patent A (P_A), n is the count of patents in the last layer linked to P_A directly or indirectly, m_i is all the possible backward paths from P_i to P_A, l_j is the number of patents along the j-th backward path from P_i to P_A, P_{ijk} is the k-th patent on the j-th backward path from P_i to P_A, and $BWDCit(P_{ijk})$ is the total number of backward citations of P_{ijk} excluding the backward citations by patents in between the first layer and layer $t-1$, where P_A is located in layer t [9].

3.2.3 Identification of main paths

The main paths in a technology domain/subdomain are identified by the patents with high knowledge persistence. These HPPs are detected from two indexes: global persistence (GP), which identifies crucial patents throughout the entire network of the domain/subdomain, and layer persistence (LP), which detects key patents within a layer. Using the LP, in addition to the GP, allows for including newer yet influential patents that might otherwise be overlooked [9]. To normalize the GP and LP, the knowledge persistence of each patent is divided by the maximum persistence value in the domain/subdomain to obtain the GP and divided by the maximum persistence value in each layer to get the LP.

The cutoff values for HPPs can be adjusted depending on the desired complexity of the main paths. A patent is categorized as an HPP when either its GP or LP is equal to or higher than its cutoff value. The GP cutoff between 0.3 and 0.5 and the LP cutoff between 0.7 and 0.9 is optimal for in-depth analysis [9]. In this thesis, the cutoff values of GP = 0.3 and LP = 0.8 are used except for the battery and electric motor domains. For these two domains, the cutoff values of GP = 0.5 and LP = 0.9 are set to prevent complicated main paths with 35 or more of HPPs within the recommended range of the cutoff values of the GP and LP.

Once HPPs are determined, the main paths are established through backward and forward searching from each HPP. The fundamental procedure for these searches involves selecting the patent that has the highest GP among the patents directly connected by citation and being cited respectively. Therefore, any direct connection between two HPPs is invariably included as a part of the main paths. The search process concludes once each path reaches a *startpoint* or *endpoint* regarding all HPPs. A patent on the main paths but not an HPP is categorized as a low persistence patent (LPP). Based on these criteria, all the main paths within the network are identified. An example of the main paths from a previous paper is shown in Figure 3.2.

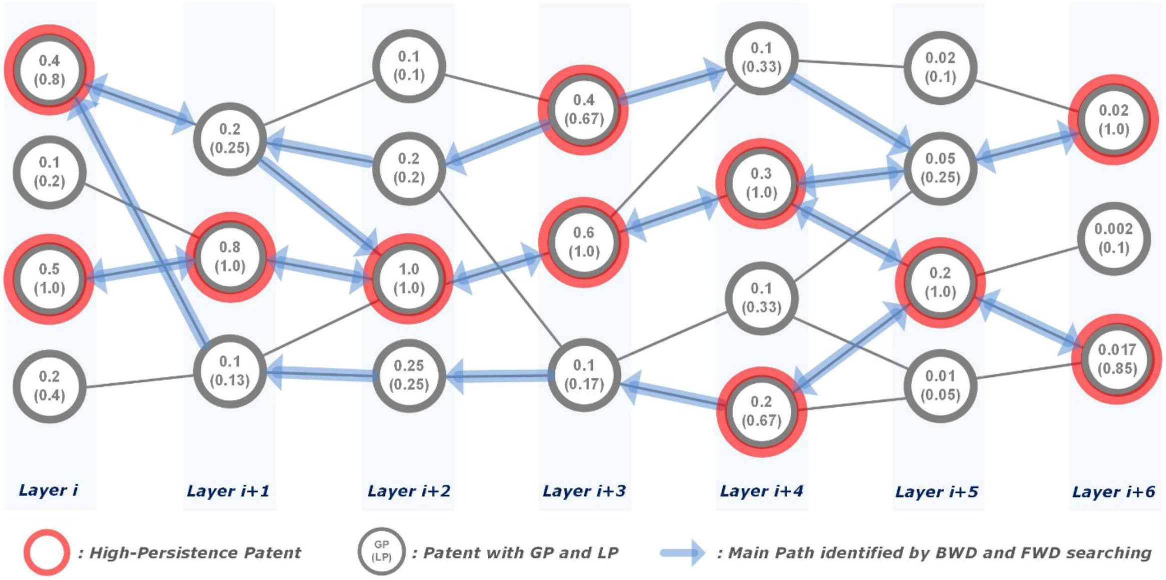

Figure 3.2: Searching backward and forward paths by Park and Magee [9]. Note: every HPP has both left and right arrows for backward and forward searches; HPP (0.2 GP and 1.0 LP) on layer *i+5* is directly connected with two HPPs on layer *i+4* and both links are chosen as main paths; if an HPP is not directly connected with other HPPs, e.g. the HPP (0.4 GP and 0.8 LP) on layer *i*, a patent which is not HPP but having the highest GP among the directly connected patents, e.g. the patent (0.2

GP and 0.25 LP) on layer *i+1*, is chosen and further searching is continued from that patent using the same algorithm.

3.3 Analysis of detected main paths

Once the main paths within each domain/subdomain have been identified, the main paths are plotted in a figure by domain/subdomain. They are analyzed, focusing on the clusters over time, technological categories, and owners of HPPs, as well as the branches of these paths. The information on the patent publication date, which is necessary to plot the patents on the main paths, the patent application domain, which is the basis of colored classification of technological categories, and the standardized current assignee, which is used to detect the trends of HPP owners, are provided in the database downloaded from patsnap. These results are also compared with the results led by Feng & Magee (2020) [5]. Furthermore, discussions are conducted considering other factors, such as patent activity trends, events in the actual world, and market shares worldwide and in the U.S. by company.

Chapter 4

Results

This chapter reports the patents on the main paths of technological development trajectory and the images of the paths of each domain and subdomain with the clusters and trends of the detected patents by domain and subdomain according to the methods described in Data and Methods. Then, cross-domain comparisons are provided.

Table 4.1 and Table A.1 to Table A.13 in Appendix A show the patents on the main paths of each domain/subdomain. Each list is in order of publication year. White cells are for HPPs, and gray cells are for LPPs. The numbers in the Node column are procedurally assigned different numbers to all patents within a domain/subdomain, and they do not affect the results or have meanings. The column of the Number shows the patent number assigned by the USPTO. The year is the publication year of each patent. The assignee's names in the Current assignee column follow the Standardized Current Assignee provided by patsnap.

Figure 4.1 to Figure 4.14 illustrate the main paths of each domain /subdomain. The patents are organized along main paths over time. Each patent is positioned according to its publication year. Each HPP is drawn with a black number within an oval surrounded by a thick line, and each LPP is drawn with a blue number within an oval surrounded by a thin line. These numbers correspond to the Node number shown in each table of each domain/subdomain (Table 4.1 and Table A.1 to Table A.13). The color inside each ellipse shows the patent technological category determined based on the application domains of each patent provided by patsnap.

As a trend for each domain/subdomain, the number of LPPs increases near the end of the main paths, and the ratio of HPPs to the nodes decreases in recent years. In addition, many recent LPPs are located on the paths derived into multiple from the most recent HPPs. Each domain/subdomain has characteristics, such as the period when many HPPs, i.e., critical technical innovations, occurred, the clusters of HPP technological categories, the division of main paths, and the variety of HPP assignees. I describe these observations by domain/ subdomain below.

4.1 Main paths of battery domain

Table 4.1: Patents on the main paths of the battery domain. Note: 34 HPPs out of 128 Nodes. The list is in order of publication year. White cells are for HPPs, and gray cells are for LPPs. The numbers in the Node column are procedurally assigned different numbers to all patents within a domain/subdomain, and they do not affect the results or have meanings. The column of the Number shows the patent number assigned by the USPTO. The year is the publication year of each patent. The assignee's names in the Current assignee column follow the Standardized Current Assignee provided by patsnap. The patents on the main paths of other domains/subdomains are shown in Appendix A.

Node	Number	Year	Current assignee	Node	Number	Year	Current assignee
49344	US3992226A	1976	ULTRA MOLD CORP	27005	US8556996B2	2013	AMPRIUS TECH INC
48717	US4169918A	1979	EVEREADY BATTERY CO INC	33303	US8455131B2	2013	POLYPLUS BATTERY CO INC
48689	US4182797A	1980	PANASONIC CORP	26838	US8557425B2	2013	FLAGSHIP ENTERPRISE CENT INC
48694	US4186247A	1980	THE RICHARDSON	33516	US8344685B2	2013	MIDTRONICS
48242	US4306002A	1981	GENERAL BATTERY	24613	US8828580B2	2014	POLYPLUS BATTERY CO INC
48125	US4304825A	1981	BELL LAB INC	33417	US8663829B2	2014	LG ENERGY SOLUTION LTD
48170	US4314008A	1982	MOLTECH POWER SYST	21774	US9123941B2	2015	POLYPLUS BATTERY CO INC
48298	US4321114A	1982	UNIV PATENTS	25648	US9112230B2	2015	BASF SE
47991	US4409302A	1983	GENERAL MOTORS CORP	24563	US9184424B2	2015	LG ENERGY SOLUTION LTD
47830	US4423125A	1983	LUCENT TECH INC | BELL TLEPHONE LAB	23263	US9368775B2	2016	POLYPLUS BATTERY CO INC

47881	US4443523A	1984	BROWN BOVERI & CO AG	31281	US9337457B2	2016	ROBERT BOSCH GMBH | SAMSUNG SDI CO LTD
47867	US4455523A	1984	NORAND CORP A CORP OF | UNOVA	17379	US9406927B1	2016	STOREDOT
47631	US4522898A	1985	BROWM BOVERI & CIE AG A GERMAN	16410	US9601779B2	2017	POLYPLUS BATTERY CO INC
47567	US4553081A	1985	UNOVA	18987	US9960465B2	2018	LG ENERGY SOLUTION LTD
47851	US4617243A	1986	KAO CORP	22358	US10084218B2	2018	LG ENERGY SOLUTION LTD
47471	US4615959A	1986	SANYO CHEM IND LTD	16176	US9985289B2	2018	BASF SE
47263	US4709202A	1987	INTERMEC	19006	US9893337B2	2018	SEEO
47297	US4702977A	1987	TOSHIBA BATTERY | MITSUBISHI PETROCHEM CO LTD	18393	US10153651B2	2018	24M TECH INC
47004	US4851305A	1989	GNB TECH	9824	US10483510B2	2019	SHAPE CORP
46905	US4916034A	1990	JOHNSON CONTROLS TECH CO	11255	US10199677B2	2019	STOREDOT
46382	US5069683A	1991	MOLI ENERGY 1990	20143	US10665848B2	2020	CPS TECH HLDG LLC
46775	US5028500A	1991	MOLI ENERGY 1990	7125	US10608463B1	2020	STOREDOT
46267	US5219680A	1993	ULTRACELL LLC	6096	US10714744B2	2020	GRP 14 TECH INC
45743	US5281492A	1994	ZTONG YEE INDAL	22363	US10770762B2	2020	LG ENERGY SOLUTION LTD
45710	US5340670A	1994	KK TOSHIBA	12543	US10632857B2	2020	SHAPE CORP
45066	US5437692A	1995	ELECTROVAYA	7205	US10549650B2	2020	STOREDOT
45737	US5443601A	1995	RGT UNIV OF CALIFORNIA	5547	US11139467B2	2021	24M TECH INC
45322	US5478674A	1995	UBE IND LTD	9833	US11211656B2	2021	SHAPE CORP
44341	US5702845A	1997	CANON KK	9848	US10886513B2	2021	SHAPE CORP
43855	US5694024A	1997	MAXIM INTEGRATED PROD INC	11908	US11054480B2	2021	MIDTRONICS
44833	US5609975A	1997	PANASONIC CORP	3016	US11152672B2	2021	CPS TECH HLDG LLC
44335	US5648187A	1997	SION POWER CORP	3688	US10910858B2	2021	24M TECH INC

43827	US5718989A	1998	GS YUASA INT LTD | AGM BATTERIES	8831	US10903498B2	2021	FORD GLOBAL TECH LLC
43948	US5800942A	1998	PANASONIC CORP	5713	US10950890B2	2021	ROBERT BOSCH GMBH
43622	US5766796A	1998	EIC LAB	5712	US10950891B2	2021	ROBERT BOSCH GMBH
43680	US5888671A	1999	SANYO ELECTRIC CO LTD	4302	US10916753B2	2021	POLYPLUS BATTERY CO INC
43725	US5869208A	1999	THE FURUKAWA BATTERY CO LTD	4308	US11211643B2	2021	PANASONIC AVIONICS CORP
43501	US5961672A	1999	SION POWER CORP	13429	US10940747B2	2021	NIO ANHUI HLDG CO LTD
42379	US6060864A	2000	KK TOSHIBA	4431	US11201374B2	2021	IERADI GIUSEPPE
42060	US6137269A	2000	CHAMPLIN KEITH S	2456	US11155150B2	2021	SHAPE CORP
43231	US6083644A	2000	SEIKO INSTR INC	860	US11335903B2	2022	GRP 14 TECH INC
42690	US6255015B1	2001	CHEVRONTEXACO TECH VENTURES	655	US11492262B2	2022	GRP 14 TECH INC
43733	US6274278B1	2001	CONSIGLIO NAT DELLE RICERCHE	713	US11498838B2	2022	GRP 14 TECH INC
42230	US6235427B1	2001	HANGER SOLUTIONS LLC	220	US11509146B1	2022	NUVOLTA TECH (HEFEI) CO LTD
41811	US6432583B1	2002	NIPPON POWER GRAPHITE CO LTD	3071	US11289701B2	2022	AMPRIUS TECH INC
40607	US6392414B2	2002	MIDTRONICS	2934	US11495793B2	2022	GRP 14 TECH INC
41996	US6537694B1	2003	MAKITA CORP	6012	US11258102B2	2022	ROBERT BOSCH GMBH
40591	US6589696B2	2003	SAMSUNG SDI CO LTD	2329	US11251494B2	2022	CANOO TECHNOLOGIES INC
41668	US6551743B1	2003	SANYO ELECTRIC CO LTD	1910	US11411418B2	2022	RAYMOND LTD
40571	US6677082B2	2004	CHICAGO UNIV OF THE | UCHICAGO ARGONNE LLC	2168	US11594793B2	2023	24M TECH INC

41133	US6783886B1	2004	MAKITA CORP	1570	US11742525B2	2023	KYOCERA CORP | 24M TECH INC
41000	US6709783B2	2004	PANASONIC CORP	1250	US11831026B2	2023	KYOCERA CORP | 24M TECH INC
40000	US6733922B2	2004	SAMSUNG SDI CO LTD	1988	US11742540B2	2023	CANOO TECHNOLOGIES INC
40696	US6964828B2	2005	UMICORE AG & CO KG	28	US11804591B2	2023	GRP 14 TECH INC
38723	US7358011B2	2008	SHIN ETSU CHEM CO LTD	658	US11855279B2	2023	AMPRIUS TECH INC
37302	US7560190B2	2009	LG ENERGY SOLUTION LTD	2250	US11646445B2	2023	POLYPLUS BATTERY CO INC
38922	US7498100B2	2009	JOHNSON MATTHEY PLC	2249	US11646444B2	2023	POLYPLUS BATTERY CO INC
33906	US7683359B2	2010	NEXEON LTD	5528	US11749834B2	2023	POLYPLUS BATTERY CO INC
35476	US7816031B2	2010	THE BOARD OF TRUSTEES OF THE LELAND STANFORD JUNIOR UNIV	6642	US11740294B2	2023	MIDTRONICS
32559	US8048571B2	2011	POLYPLUS BATTERY CO INC	9443	US11650259B2	2023	MIDTRONICS
35771	US7997367B2	2011	TOYOTA JIDOSHA KK	1699	US11646472B2	2023	POLYPLUS BATTERY CO INC
36464	US7906238B2	2011	SICONA BATTERY TECH PTY LTD	1496	US11833914B2	2023	RIVIAN IP HLDG LLC
29073	US8202649B2	2012	POLYPLUS BATTERY CO INC	1624	US11824217B2	2023	HYUNDAI MOTOR CO LTD | KIA CORP
33434	US8277974B2	2012	IONBLOX INC	2118	US11668779B2	2023	MIDTRONICS

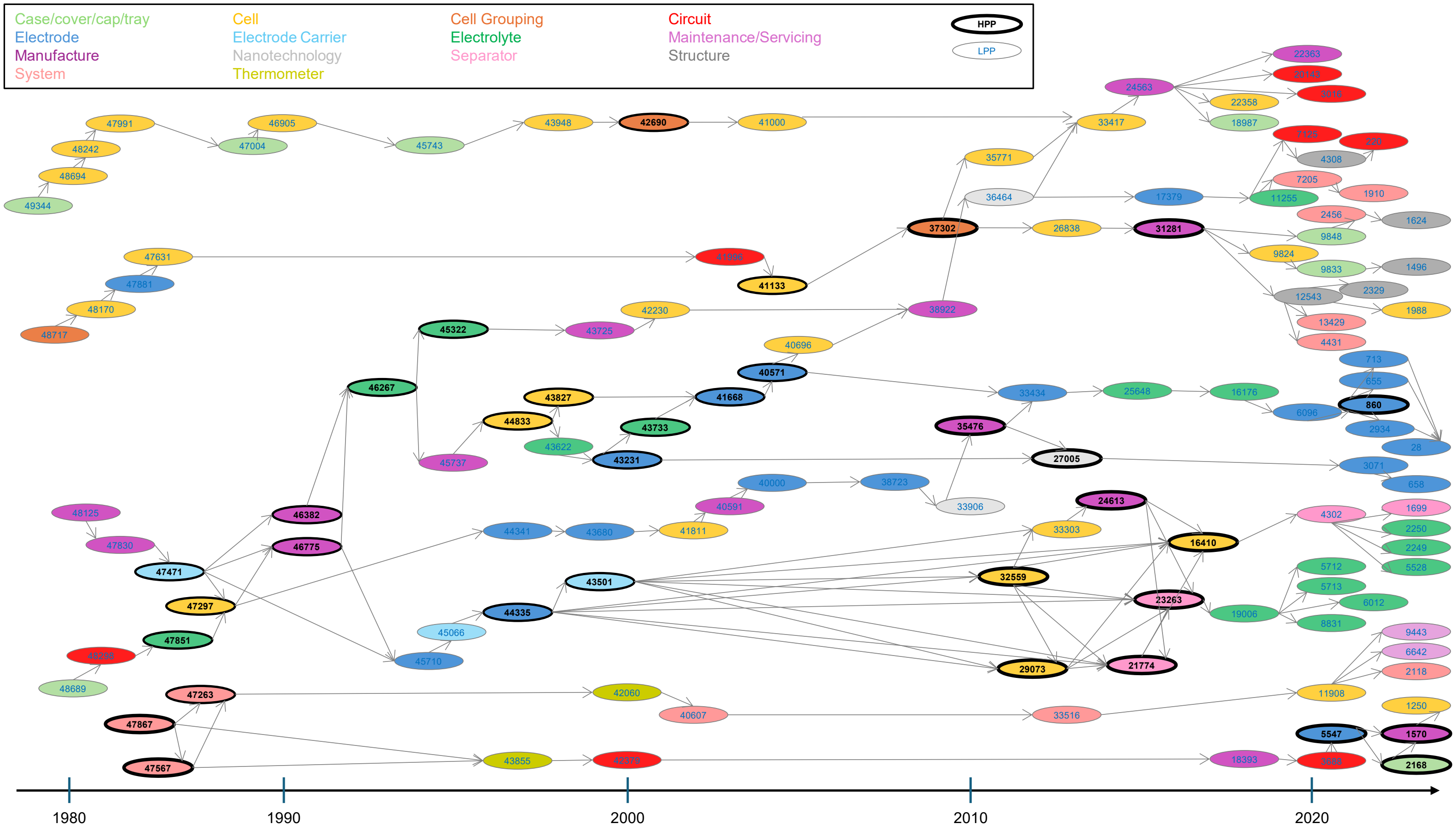

Figure 4.1: The main paths of the battery domain. Note: The patents are organized along main paths over time. Each patent is positioned according to its publication year. Each HPP is drawn with a black number within an oval surrounded by a thick line, and each LPP is drawn with a blue number within an oval surrounded by a thin line. These numbers correspond to the Node number shown in each table of the same domain/subdomain. The color inside each ellipse shows the patent technological category determined based on the application domains of each

patent provided by patsnap. Figure 4.2 to Figure 4.14 follow the same rules.

Regarding the battery domain, many HPPs occurred from the mid-1980s to 2023. The HPPs include diverse technological categories: cell (7 HPPs), electrode (6 HPPs), manufacture (6 HPPs), electrolyte (4 HPPs), and other (11 HPPs), and there are no particular trends in categories over time. The paths after the late 2010s are divided into about 9 streams: some of which connected from recent HPPs are innovation clusters of the electrode or electrolyte, but not limited to them. These suggest that in the development of battery technology, various technological categories are crucial and that various technological developments are progressing in parallel rather than developing from a specific key innovation. Furthermore, these trends have continued over the period covered and may continue into the future.

The assignee of the most HPPs is Polypus Battery Company (PolyPlus), which has 6 HPPs, 18% of the HPPs. Following PolyPlus, 24M Technologies holds 3 (9%) HPPs. The rest of the HPP assignees own 1 or 2 HPPs, which means the assignees are rich in diversity, and the battery key innovations are not dominated by a few players. It can be said that the battery field is open to new entrants, including startups. Focusing on the HPPs cited by many HPPs, the top 3 are Node 44335 of Sion Power, cited by 6 HPPs; Node 43501 of Sion Power, cited by 5 HPPs; and Node 32559 of PolyPlus, cited by 4 HPPs in order. These HPPs are on the paths leading to recent electrolyte and separator innovations. However, considering the trends in the previous paragraph, it is too early to say whether innovations in electrolytes and separators will become more important in the battery field in the future (Table 4.1, Figure 4.1).

4.2 Main paths of battery subdomains

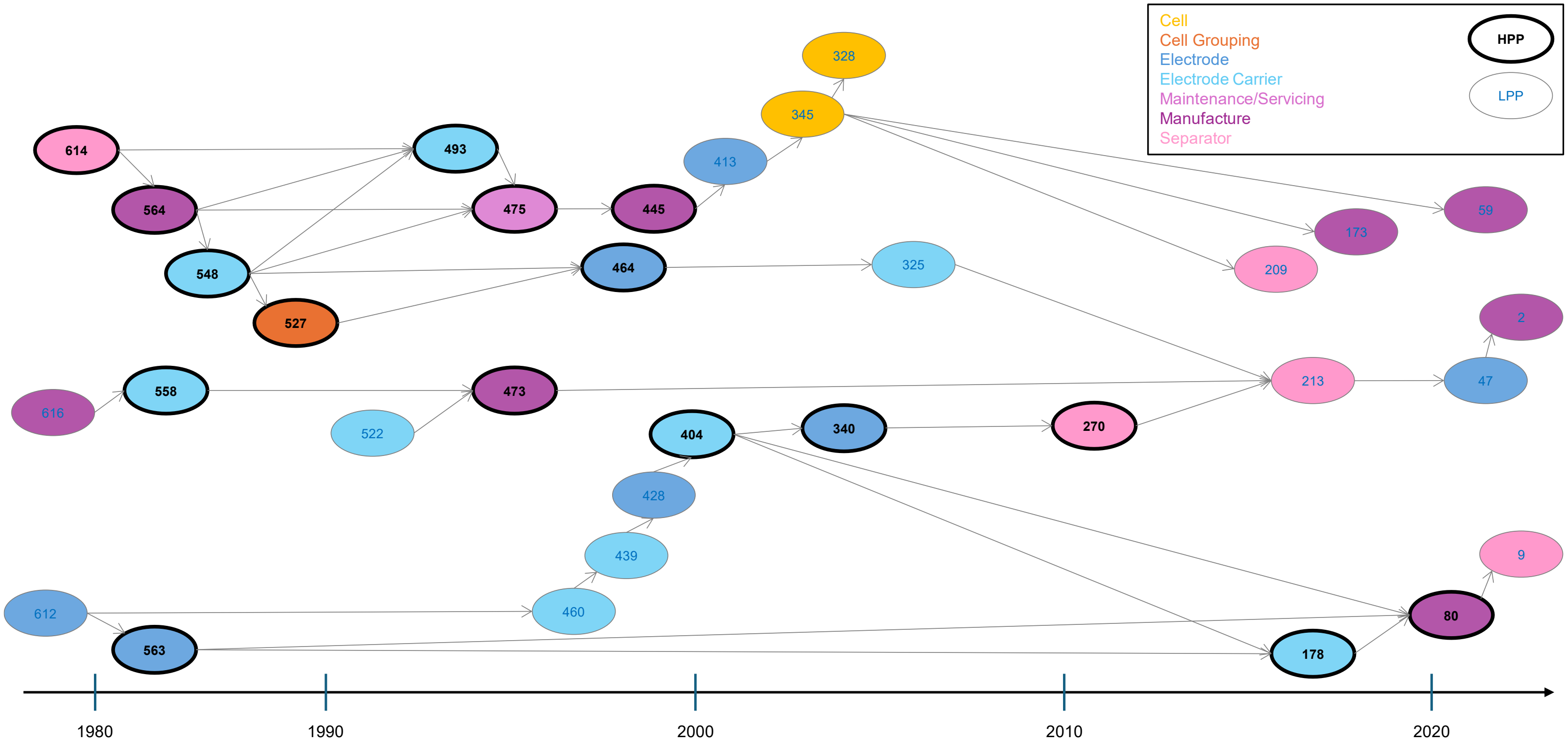

Figure 4.2: The main paths of the lead acid subdomain.

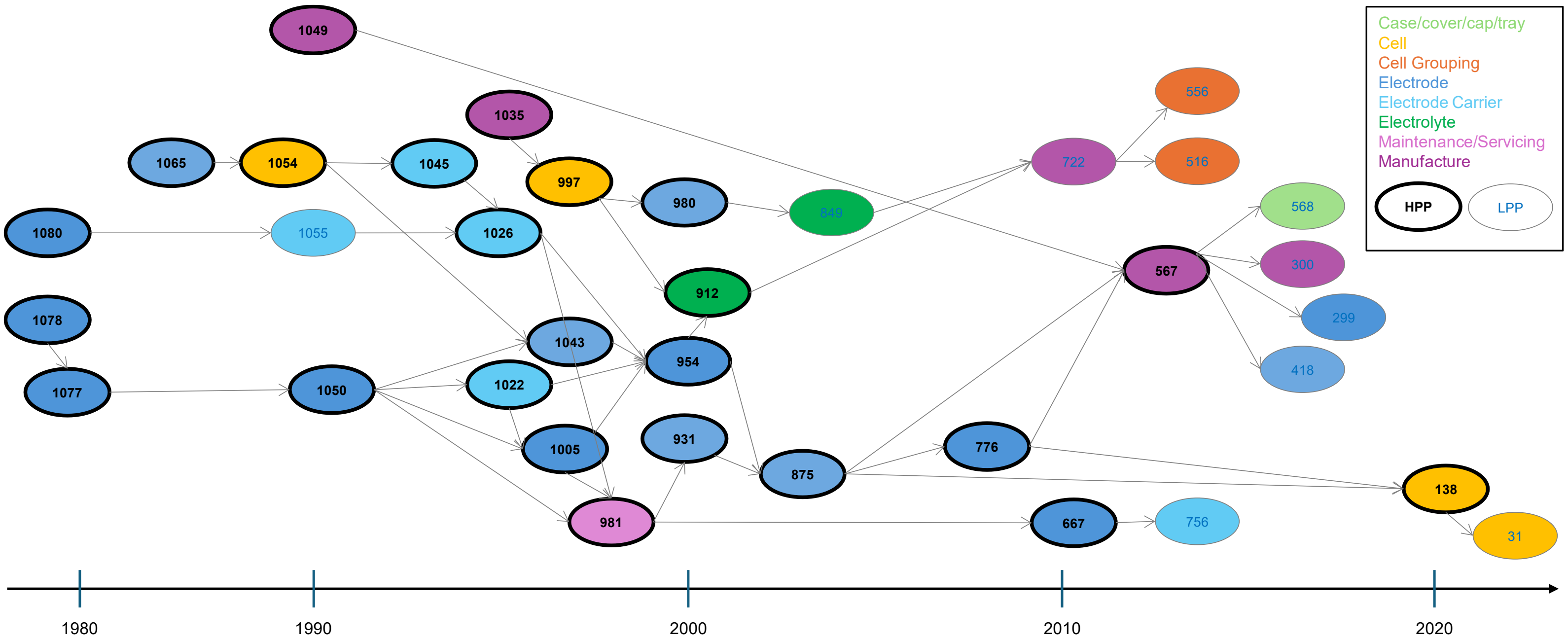

Figure 4.3: The main paths of the nickel battery subdomain.

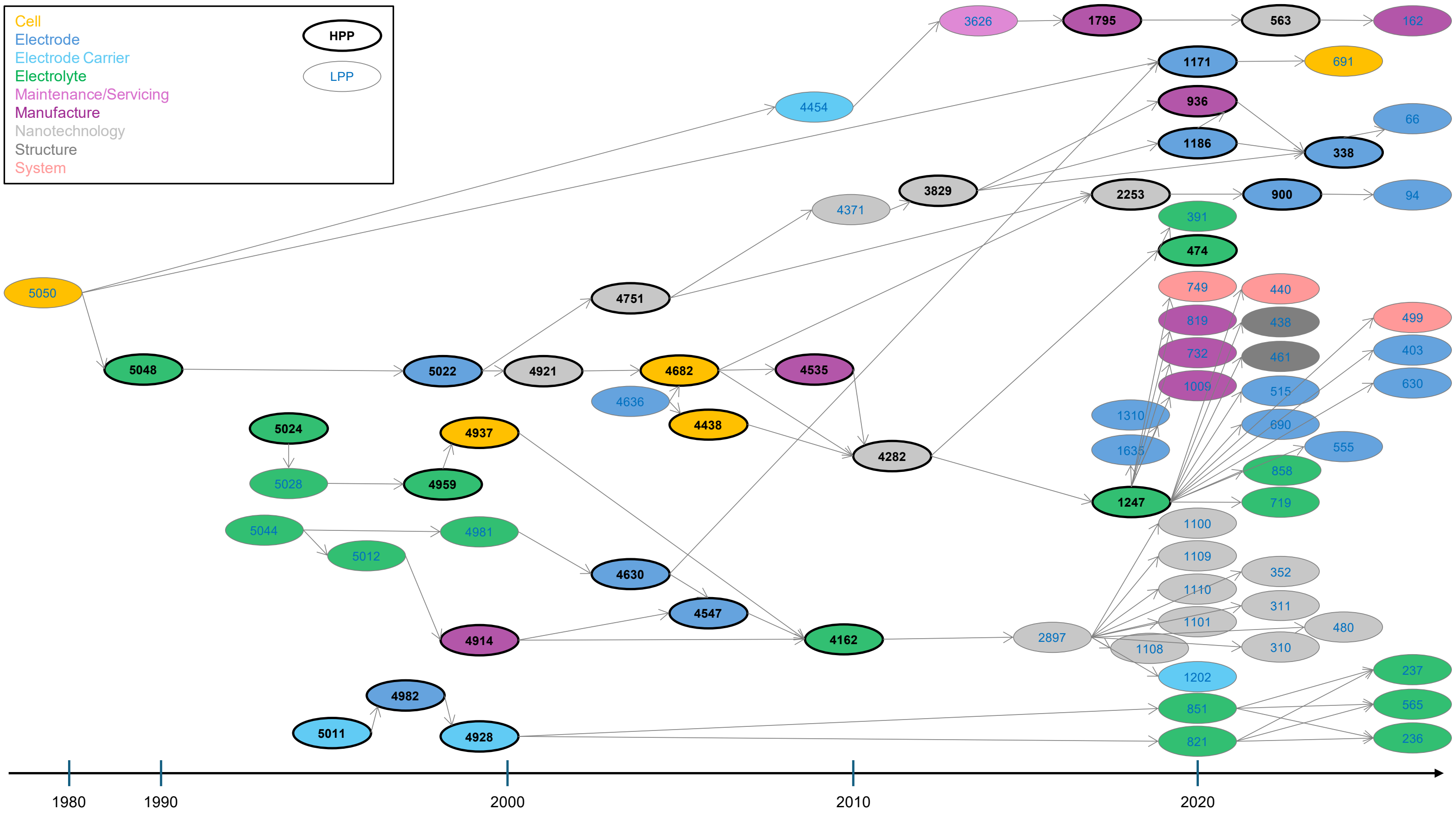

Figure 4.4: The main paths of the lithium-ion battery subdomain.

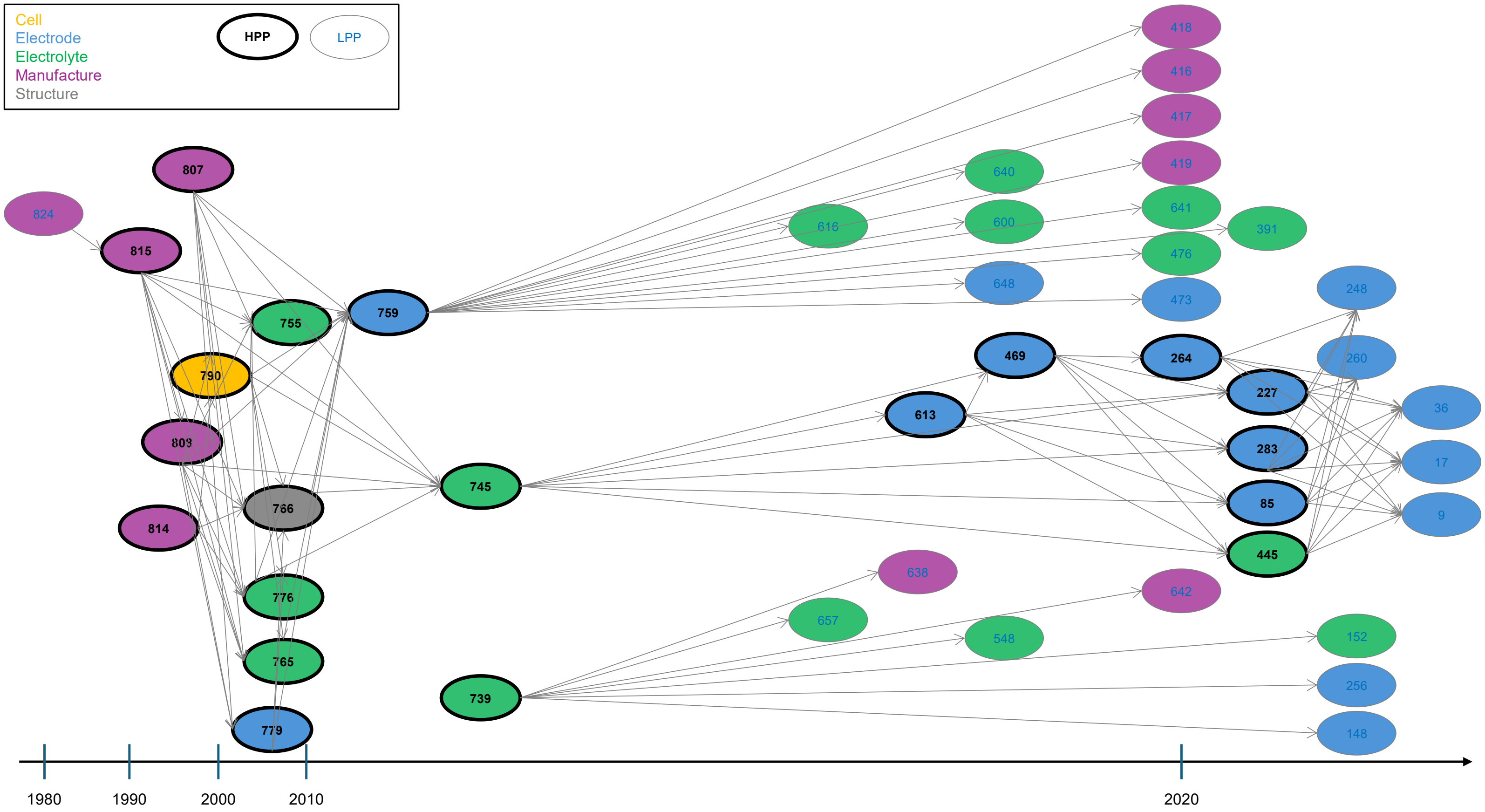

Figure 4.5: The main paths of the solid-state battery subdomain.

Looking into the subdomains of the battery domains, while there were many HPPs between 1976 and 2000 for the lead acid battery subdomain and between 1976 and the mid-2000s for the nickel battery subdomain, the HPPs of lithium-ion and solid-state batteries were born from the mid-1990s to 2023. The main HPP technological categories of all battery subdomains include electrode/electrode carrier and manufacture, though no common ordering relationship between these two categories can be observed from the main paths. These two categories can continue to be the key innovations, considering the historical stability of their importance on the main paths and the development and challenges of batteries described in the Literature Review Chapter. Electrolyte innovations were critical in the lithium-ion battery subdomain and solid-state battery subdomain, and the nanotechnology category was as well for the lithium-ion battery subdomain. Electrolyte innovations should become further critical for lithium-ion and solid-state batteries, considering that solid-state lithium batteries with solid-state electrolytes have been regarded as one of the most promising batteries [63], though predicting this future trend from the main paths is challenging. Nanotechnology will also increase its importance in the lithium-ion battery field because the share of nanotechnology HPPs has been increasing, as well as its significance in improving the performance of lithium-ion batteries with advanced anode materials [64].

The recent paths are divided into 3 to 4 streams, except for the lithium-ion battery subdomain, which has about 8 streams. Among the subdomains with 3 to 4 streams, the main paths in the solid-state battery domain have three explicitly important patents that led to recent innovations: Node 759, Node 745, and Node 738 in Table A.4 and Figure 4.5. This suggests that solid-state battery technology has some patents that can serve as a gateway to future innovations compared to other battery subdomains. The recent major technological category trends in these streams are manufacture for the lead acid battery, cell/cell grouping for the nickel battery, electrode, electrolyte, manufacture, and nanotechnology for the lithium-ion battery, and electrode, electrolyte, and manufacture for the solid-state battery. 13 patents are shared by the patents on the main paths of the battery domain and lithium-ion battery subdomain, but no other overlaps exist among the main paths of the battery domain and four battery subdomains. It shows that lithium-ion battery innovations are relatively important for the whole battery innovations.

Toda Kogyo Corp. has HPPs both in the nickel and lithium-ion battery subdomain, and Martin Marietta Energy Systems holds HPPs both in the lithium-ion and solid-state battery subdomain, but other companies do not own HPPs of more than one subdomain. If an entity makes important innovations in multiple fields, it can have a certain competitiveness in multiple fields. On the other hand, as described below for each subdomain, Toda Kogyo Corp. and Martin Marietta Energy Systems have not necessarily brought about many important innovations in each battery field, and it is unlikely that much synergy effect can be expected by creating important innovations in multiple battery fields.

Regarding the lead acid battery subdomain, California Institute of Technology, Ensci, Inc., GS Yuasa International Ltd., and CPS Technology Holdings LLC. have the largest HPPs, 2 (13%) HPPs, respectively. The HPPs most cited by HPPs are Node 548, cited by 4 HPPs, and Node 564 and 404, cited by 3 HPPs. Both assignees and citations between HPPs are distributed in the lead acid battery subdomain (Table A.1, Figure 4.2).

As for the nickel battery subdomain, Panasonic has 6 HPPs, 25% of the HPPs, and Duracell U.S. Operations, Inc. has 4 (17%) HPPs. The rest of the HPP assignees own 1 or 2 HPPs. The patents on the main paths and most cited by HPPs are Node 1050, cited by 4 HPPs, and Node 875, cited by 3 HPPs. Though Panasonic seems to be a key player, both of these patents are not owned by Panasonic, and, furthermore, the HPPs of Panasonic were published from 1995 to 2000. These suggest that Panasonic does not have a strong influence on current innovation, though it grips key innovations in the development history and that key innovators of nickel batteries have increased diversity (Table A.2, Figure 4.3).

The assignees and cited-citation relationship in the lithium-ion battery subdomain are diverse. While Amprius Technologies owns 4 (14%) HPPs, the other assignees hold 2 or fewer HPPs. The biggest number of citations by HPPs is 3 of Node 4682 and Node 3829 (Table A.3, Figure 4.4).

A few companies share most HPPs in the solid-state battery subdomain; QuantumScape has 6 (30%) HPPs, Cymbet Corporation has 4 (20%) HPPs, and Martin Marietta Energy Systems has (15%) HPPs. The most cited HPPs by HPPs are Node 815, owned by Tufts University, which was cited by 8 HPPs, and Node 808 and Node 807, held by Martin Marietta Energy Systems, which are cited by 8 and 7 HPPs, respectively. These highly cited HPPs are located at the dawn of the main paths in this subdomain, and HPPs in the last decade are mostly by

QuantumScape. This indicates that QuantumScape dominates the critical innovations of the solid-state battery (Table A.4, Figure 4.5).

4.3 Main paths of ultra capacitor domain

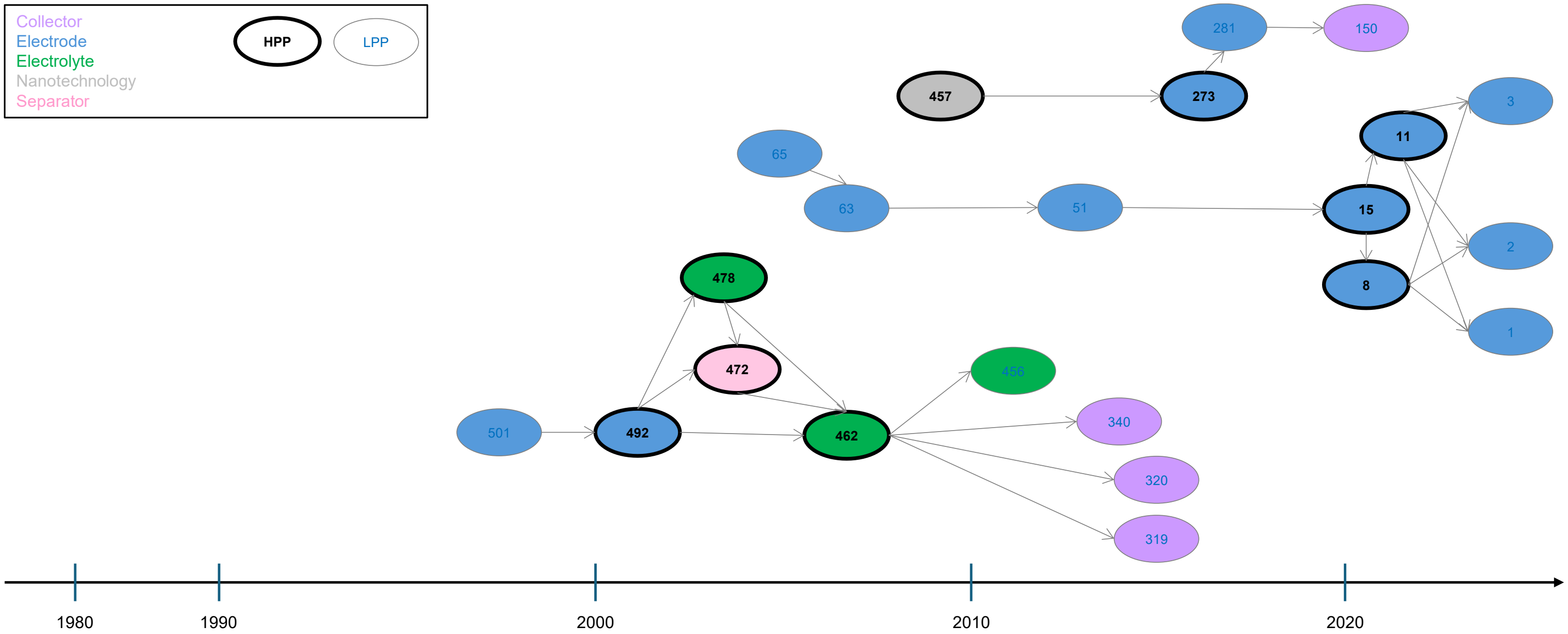

Figure 4.6: The main paths of the ultra capacitor domain.

Most HPPs in the ultra capacitor domain have been published since 2000, comparatively new. There are 3 separate main path branches: One of them is a cluster of electrode innovations; another one is a mix of nanotechnology and electrode HPPs; and the rest is a mix of electrode, electrolyte, and separator HPPs. Since the last branch ended in 2015, future main paths in this domain can grow from the first two branches, and the focus of critical innovations can concentrate on electrode innovations. The top 2 assignees, KYOCERA AVX Components Corporation and Nanotek Instruments Group, LLC., have 3 (33%) and 2 (22%) HPPs, respectively. Looking into the relationships between the branches and HPP assignees, all HPPs in the second branch are held by KYOCERA AVX Components Corporation, and all HPPs in the first branch are owned by Nanotek Instruments Group, LLC. Therefore, it is suggested that critical innovations of ultra capacitors are dominated by these two companies and that each company is proceeding with development independently from the other. The HPPs often cited by HPPs are Node 492, cited by 3 HPPs, and Node 478 and Node 15, cited by 2 HPPs. However, both are located in the branch that stopped in 2015, which suggests that these two HPPs be not further critical in the future (Table A.5, Figure 4.6).

4.4 Main paths of battery management system domain

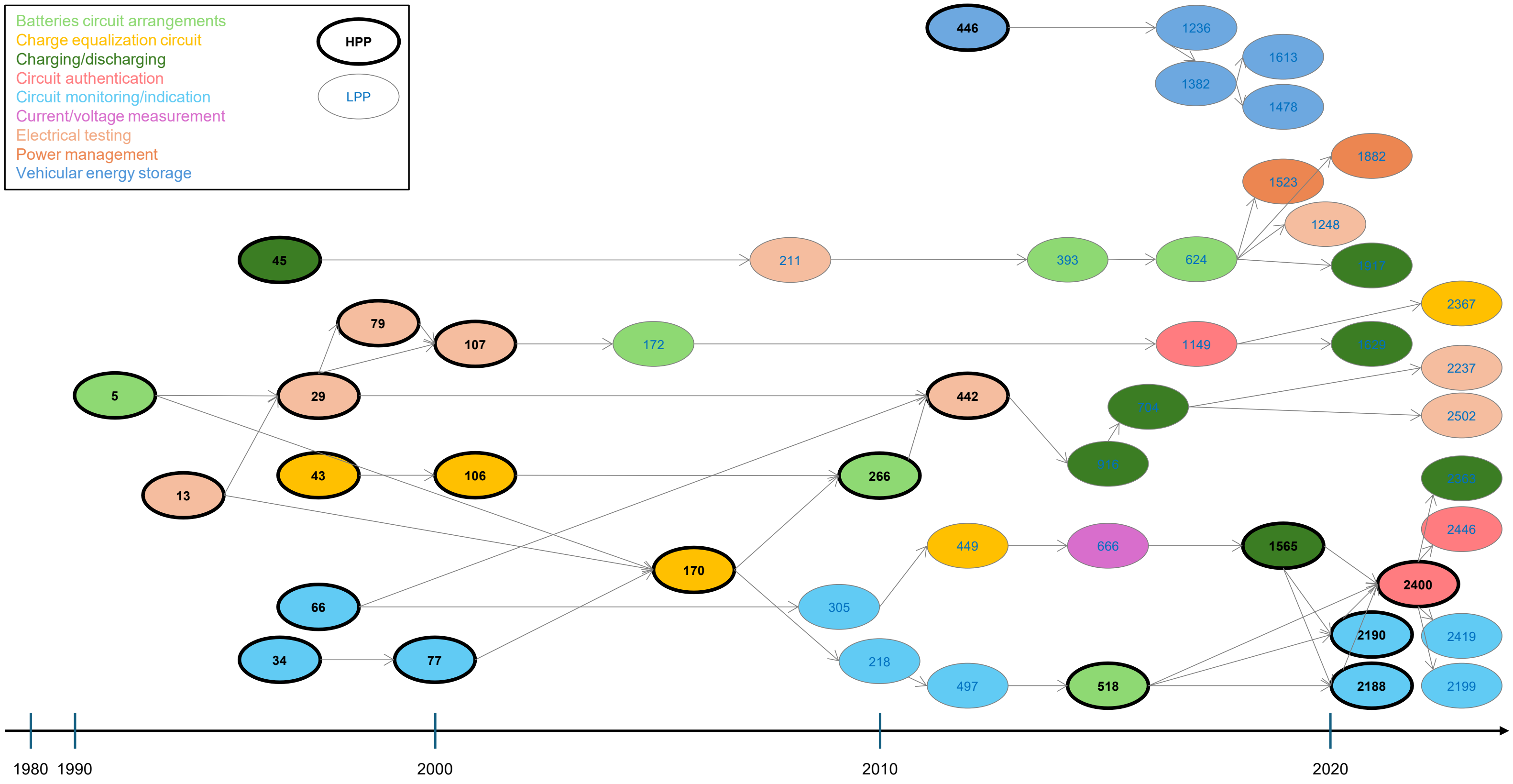

Figure 4.7: The main paths of the battery management system domain.

The HPPs in the battery management system subdomain were published after 1990. The technological categories are diverse, though electrical testing, circuit monitoring/indication, and charge equalization circuit categories were the majority until the middle. The recent paths are divided into 5 clusters; one is composed only of vehicle energy storage patents, and the rest are a mixture of various categories. These indicate that innovations in various categories are critically required to improve the performance of battery management systems and that comprehensive strength is essential to develop a competitive battery management system. No assignee is dominant; the assignee owning more than 2 HPPs is only International Components Corporation, but it is only 15% of HPPs. Node 29, Node 518, and Node 1565 are cited by 3 HPPs, and no patents are cited by more than 3 HPPs (Table A.6, Figure 4.7).

4.5 Main paths of electric motor domain

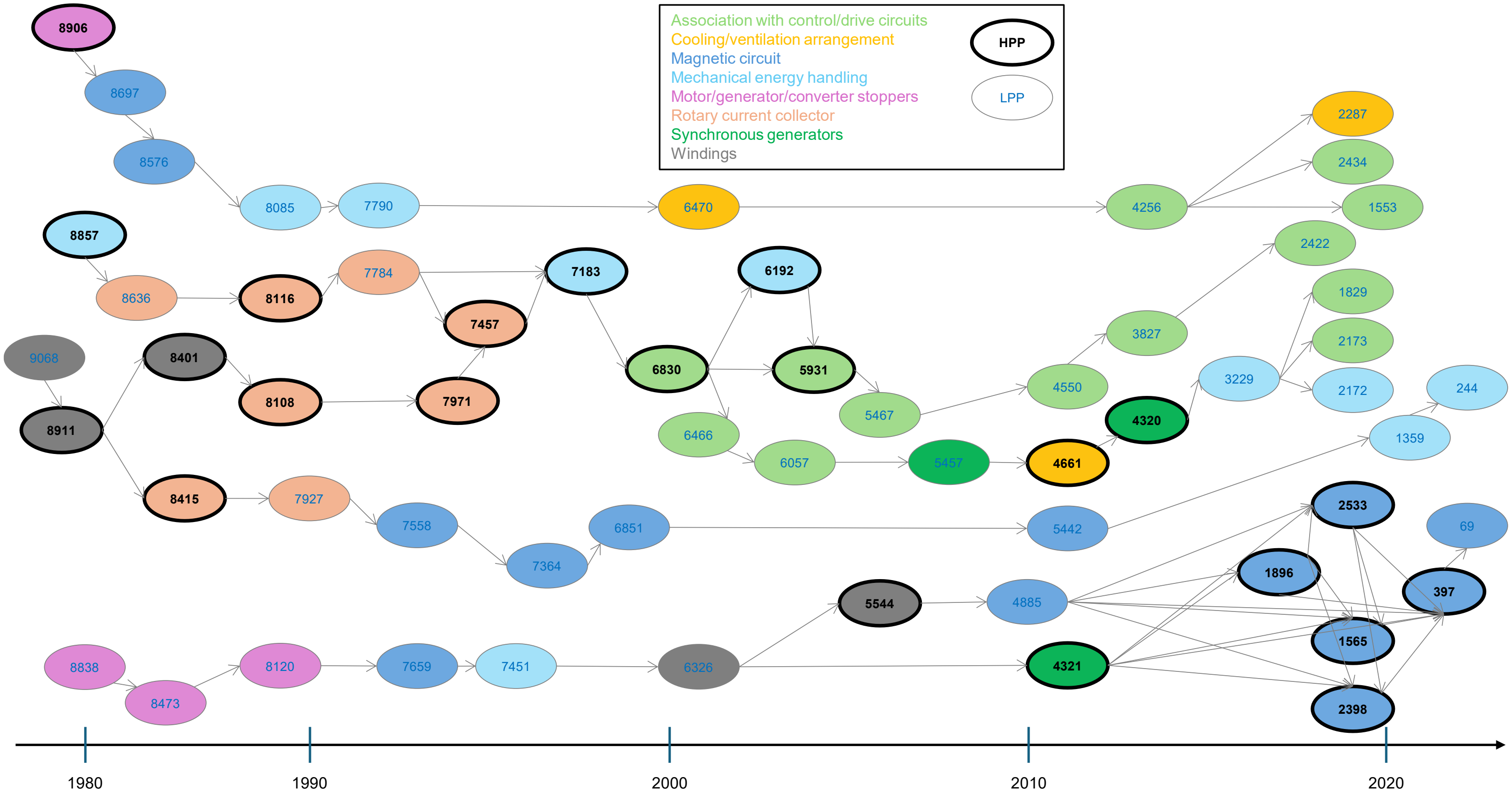

Figure 4.8: The main paths of the electric motor domain.

The HPPs in the electric motor domain are distributed constantly from 1976 to 2023. While the rotary current collector category was dominant during the first half, the magnetic circuit category has been dominant in the last decade. Though only 2 HPPs are categorized as association with control/drive circuits, 3 of the 5 recent main path clusters are mainly related to it, and the rest are about mechanical energy healing and magnetic circuits. The recent HPPs are concentrated in the cluster of the magnetic circuit category. Though this trend might not be stable, it seems to reflect the popularity of permanent magnet motors coming from its advantage. Further suggestions are described in Section 4.6.

Linear Lab holds 5 (23%) HPPs, while other assignees have a maximum of 2 HPPs. The whole HPPs of Linear Lab are classified as the magnetic circuit category, and they were published in 2017 or after, whereas no other assignees hold HPPs published after 2015. The most cited patents by HPPs on the main paths are Node 4321 and Node 4885, cited by 5 HPPs, and Node 1896, cited by 4 HPPs. All of them are located on the stream of the magnetic circuit category. Though Node 4885 of Danfoss Power Solutions is an LPP, it is one of the most cited patents by HPPs. From these observations, the recent critical innovations focus on permanent magnet motors and are dominant by Linear Lab, which can suggest that the electric motor market is getting monopolized where no other players occupy a sufficiently important position (Table A.7, Figure 4.8).

4.6 Main paths of electric motor subdomains

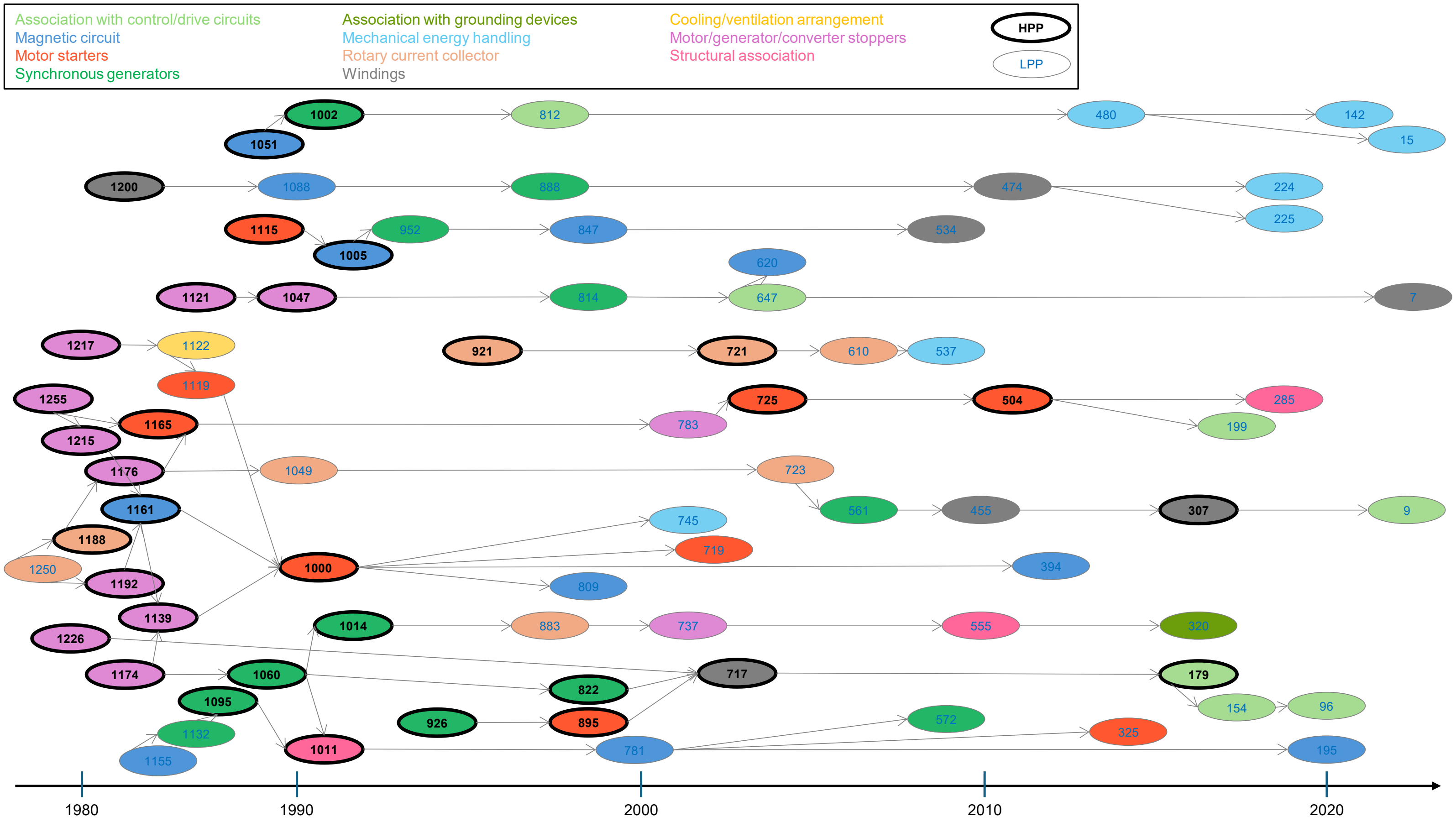

Figure 4.9: The main paths of the DC motor subdomain.

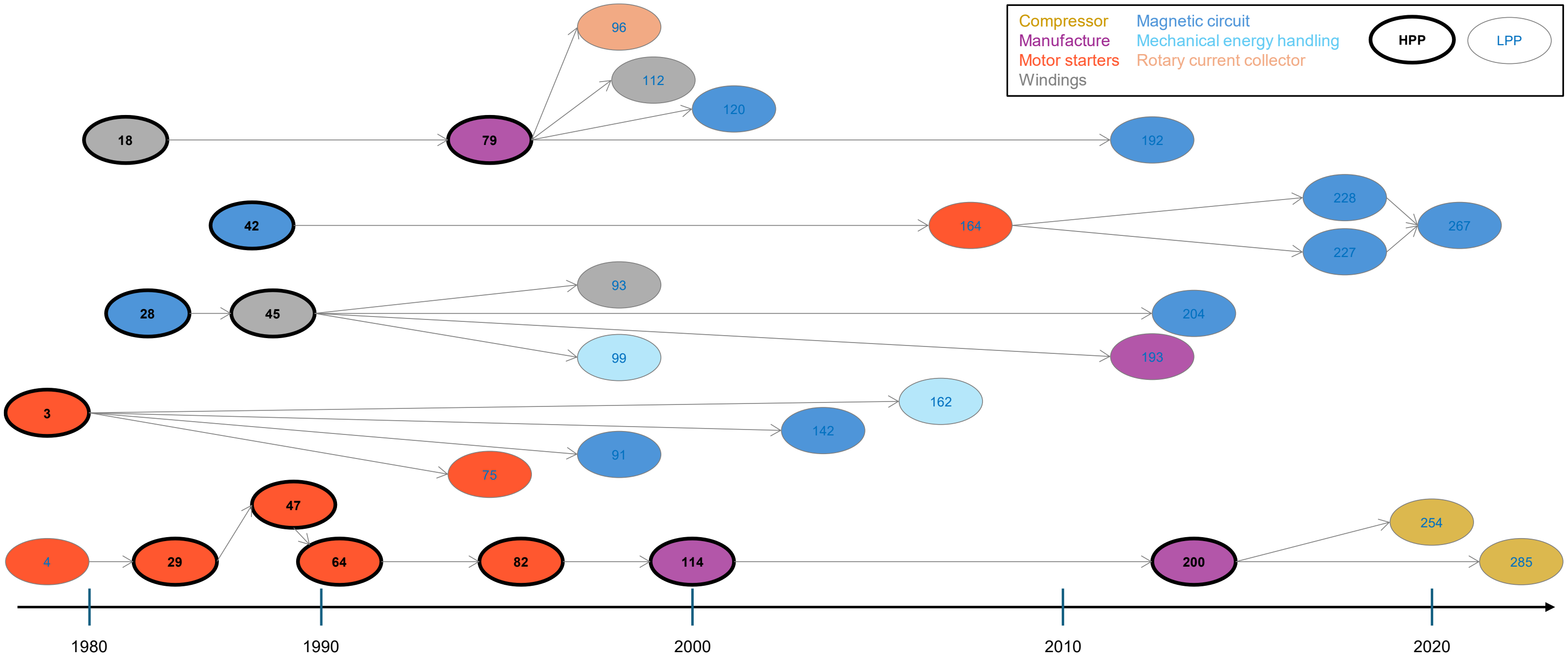

Figure 4.10: The main paths of the induction motor subdomain.

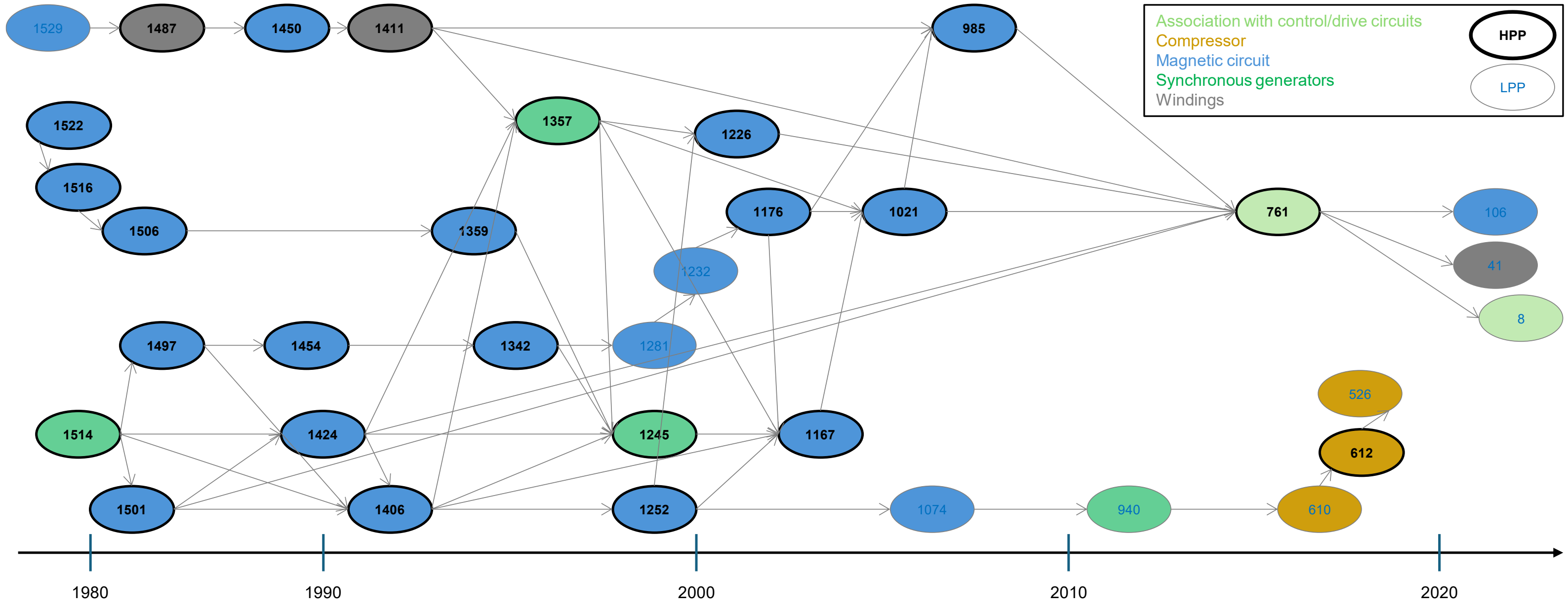

Figure 4.11: The main paths of the permanent magnet motor subdomain.

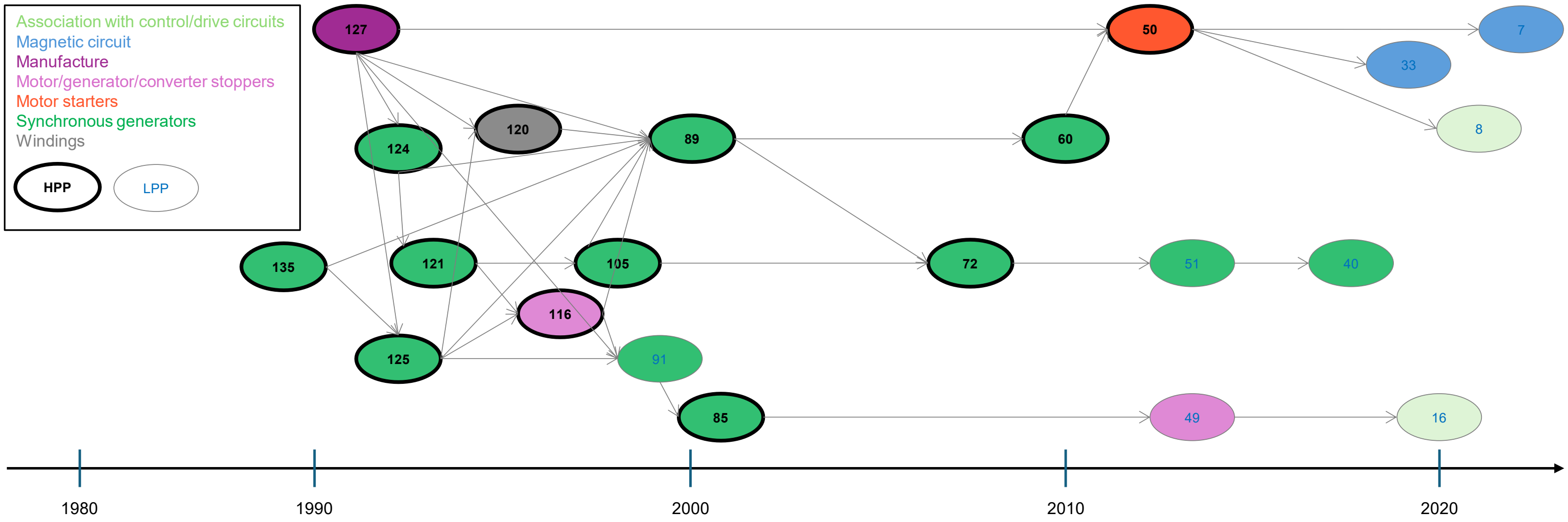

Figure 4.12: The main paths of the switch reluctance motor subdomain.

Looking into the subdomains of the electric motor domains, while there were most HPPs between 1976 and around 2000 for the DC motor and induction motor subdomains, the HPPs of the permanent magnet motor subdomain are distributed from 1976 to 2023 constantly, and HPPs of switch reluctance motor are concentrated from 1990 to 2010. The fact that HPPs have occurred until recently only in the permanent magnet motor subdomain can indicate that permanent magnet is considered the most hopeful electric motor. This is consistent with the observation by Khan (2024) that the application of permanent magnet motors brings strong performance in driving range enhancement [65]. The clusters of HPP technological categories of each subdomain have different characteristics, and no common technological development is observed from the main paths. General Electric Company has at least one HPP in each subdomain except for the switch reluctance motor subdomain. It might be the result of the long experience of energy-electrifying of General Electric Company [66] [67]. The following assignees have HPPs from 2 subdomains: BLACK+DECKER (the DC motor and permanent magnet motor subdomain), DENSO and Emerson Electric (the permanent magnet motor and switch reluctance motor subdomain), FANUC, Hitachi, and Mitsubishi Electric (the induction motor and permanent magnet motor subdomain). However, These companies do not have strong an influence in multiple subdomains regarding innovation except for Hitachi, which suggests that covering multiple subdomains' HPPs does not necessarily enhance the market-leading power of the company.

Regarding the DC motor subdomain, most HPPs were related to motor/generator/converter stoppers at the beginning and, later, motor starters and synchronous generators. The main paths for the last decade have about 11 streams; 5 are completely independent, and the technological categories are diverse. Considering that 27 HPPs out of 33 HPPs in total are published before 2000, the critical innovations of DC motors happened early, and recent research seems to focus less on this field. General Electric Company, Sony Corporation, PAPST LICENSING GmbH & Co. KG are the assignees of 3 HPPs, but each share of HPPs is only 9%. The only HPP cited by more than 2 patents is Node 1060, cited by 3 HPPs. These show that DC motor technology has been established by a mix of different players (Table A.8, Figure 4.9).

In the induction motor subdomain, there are 5 independent main paths, and only one of them includes over 2 HPPs, on which motor starters and then manufacture are the technological categories of HPPs. Similar to the DC motor subdomain, since 11 HPPs out of 12 HPPs in total were published in 2000 or before, recent research does not seem to focus on induction motors. The only company with multiple HPPs is Hitachi, which has 3 (25%) HPPs. All the HPPs held by Hitachi are based on innovations before 1990, which suggests that Hitachi does not necessarily lead the recent innovations in this field. No HPPs are cited by more than 2 HPPs, though each HPP is often cited by another company's HPP in this subdomain. This suggests that though the critical innovation of induction motors is not exclusive, there are some independent technological developments as there are 5 independent branches (Table A.9, Figure 4.10).

The HPPs in the permanent magnet motor subdomain are dominated by magnetic circuit technology. The main paths were consolidated into 2 branches. Hitachi, General Electric, Toshiba, and Panasonic have 2 (8%) HPPs, respectively, but the variety of the assignees is high. Node 1514, Node 1424, Node 1406, and Node 1357, most cited by HPPs, are connected to 4 forward HPPs. Compared to other subdomains of electric motors, the main paths are intertwined like a mesh, citing the patents of other assignees. It suggests that the innovations of permanent magnet motors are well published as patents and that companies are eager to develop better permanent magnet motors referencing their competitors' innovations (Table A.10, Figure 4.11).

In the switch reluctance motor subdomain, most HPPs belong to the synchronous generators category over time, with 3 recent branches of the main paths. Since the most recent patent on each main path does not belong to the synchronous generators category except for one, future critical innovations might happen in another technological category. About a half share of HPPs is had by the top 3 assignees: Emerson Electric with 3 (23%) HPPs, Pacific Scientific Company with 2 (15%) HPPs, and Baldor Electric Company with 2 HPPs. Given that the HPPs owned by Emerson Electric are dispersed over the period in which the HPPs of switch reluctance motors occurred, it can be suggested that Emerson Electric has consistently led innovation in this field. Node 127 of the manufacture technological category by Pacific Scientific Company is cited by 5 HPPs. Next, Nde 125 is cited by 3 HPPs (Table A.11, Figure 4.12).

4.7 Main paths of power electronics domain

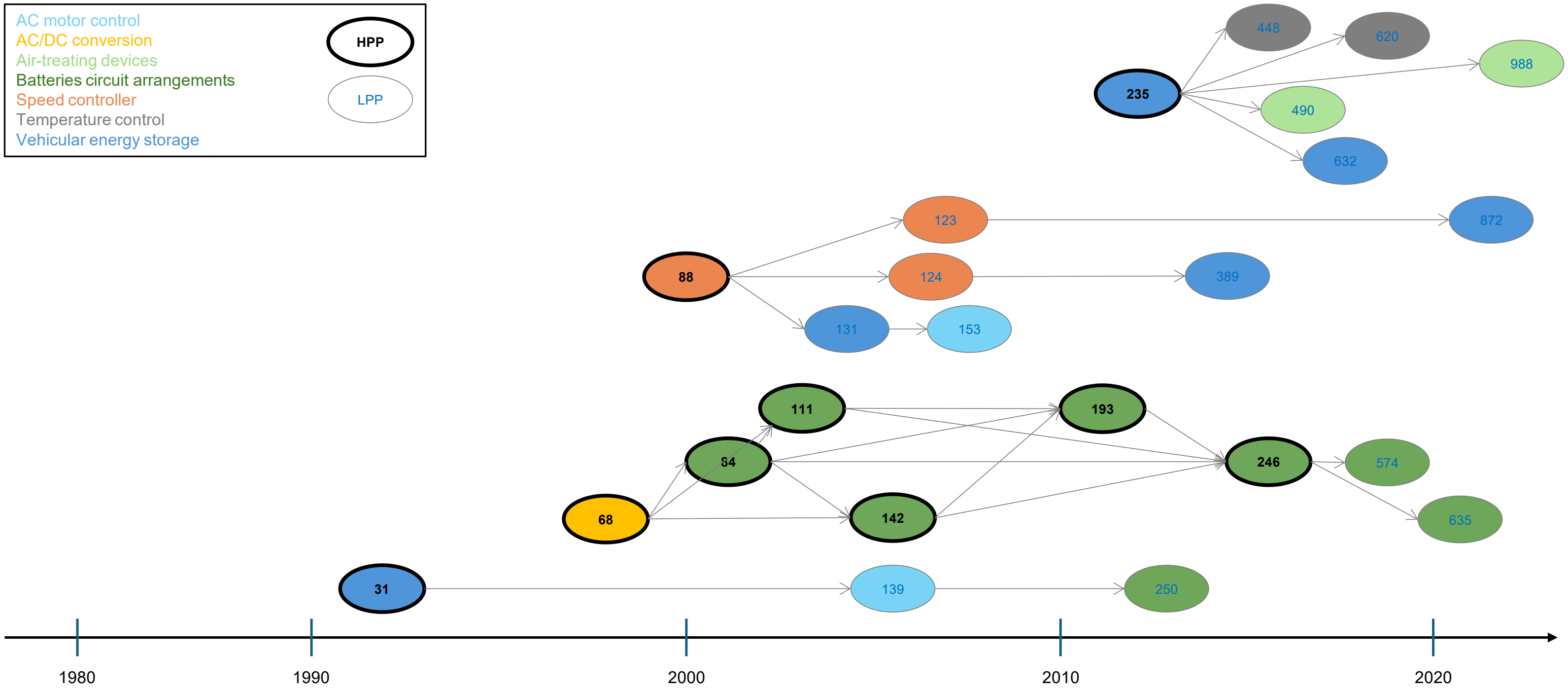

Figure 4.13: The main paths of the power electronics domain.

The HPPs in the power electronics domain are concentrated after 1990. There are 4 independent branches of main paths with different starting years, which suggests that critical innovations have occurred in independent lines in each era, and one of them, the second oldest, has two-thirds of HPPs that are mostly categorized as battery circuit arrangements. General Electric Company has 6 HPPs, which occupy 67% of HPPs. The HPPs cited by more than 2 HPPs are Node 84 and Node 68, both owned by General Electric Company. In fact, the 6 HPPs of General Electric Company, including these HPPs cited by more than 2 HPPs, are located in the second oldest branch, and the rest of the patents in the second oldest branch are also owned by General Electric Company. These observations suggest that General Electric Company has been generating a series of important and independent innovations for more than 20 years in the power electronics field (Table A.12, Figure 4.13).

4.8 Main paths of heat pump domain

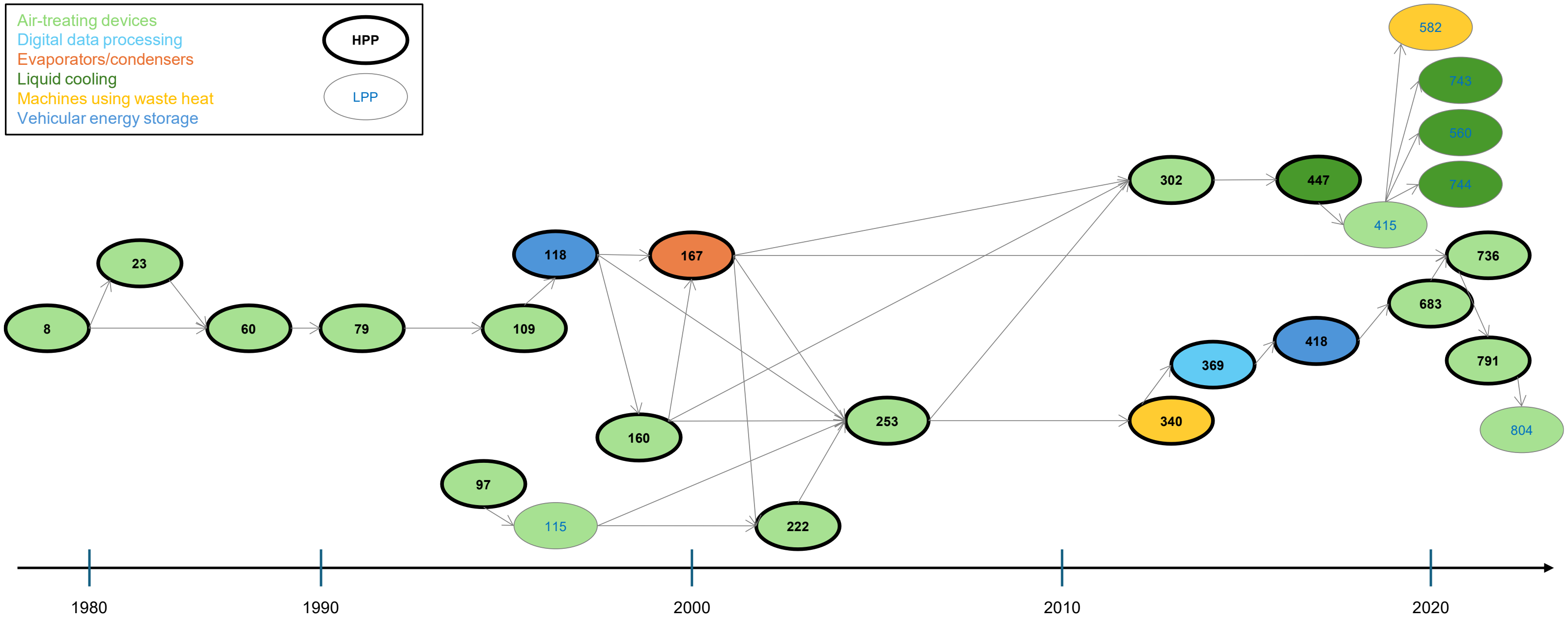

Figure 4.14: The main paths of the heat pump domain.

The heat pump domain has HPPs constantly from 1976 to 2023. Air-treating devices have been the dominant technological category (13 HPPs out of 19 HPPs in total) throughout this period. Patents on the main paths are well-connected without explicit branches. The most cited patents by HPPs are Node 167, cited by 4 HPPs, and Node 118 and 160, cited by 3 HPPs. DENSO has 4 (21%) HPPs, and Hanon Systems, Kia, and Hyundai Motor have 3 (16%) HPPs, respectively, whereas other assignees own only an HPP. Though major automotive companies dominate the critical innovations, the players seem to work collaboratively. For example, Node 369, an HPP of Hyundai Motor, Kia, Doowon Climate Control, and Hanon Systems, is cited by Node 418, an HPP of DENSO, which is cited by Node 683, an HPP of Hyundai Motor and Kia. In other words, it is suggested that the innovations of heat pumps are well-published as patents, which creates an environment that is open and promotes innovations (Table A.13, Figure 4.14).

4.9 Cross-domain comparisons of main paths

Comparing the main paths of each domain, in some domains, HPPs are constantly distributed over time, while in other domains, such as the ultra capacitor, battery management system, and power electronics domains, HPPs are concentrated in the latter half of the period. Main paths are separated into branches in most domains, but no consistency was observed in the number of branches, the growth of branches, or the relationship with technological categories.

The overlap of the HPP between domains happened only with a patent classified both in the battery management system and power electronics domains. The main paths are independent for each domain, even with the highest overlap of the patent sets of the battery and battery management system domains shown in Table 3.2. It can be said that the overlap that is high only for one domain, 52.7% with batteries for battery management systems but only 2.7% with battery management systems for batteries, does not cause the similarity of the main paths. It also suggests that critical innovations for each domain happen with research focusing on the domain-specific technological area compared to that covering wide areas.

As for the assignees, the power electronics HPPs are majority owned by one company, and more than 50% of HPPs in the ultra capacitor and heat pumps domains are owned by a few companies. This suggests that dominant companies lead critical innovations in these domains and that it can take time for other companies to take a particular market share. Additionally, in most cases, the research topics of the HPPs owned by these dominant players are the main technological categories in the main path, as Feng & Magee (2020) described [5], which can help companies and researchers choose research themes for the next generation of BEVs. In contrast, in the rest of the domains, HPPs are shared among various assignees. Feng & Magee (2020) examined the assignees of HPPs in the lithium-ion battery and permanent magnet motor subdomains. They calculated how many HPPs the companies, or parent companies if the assignees are subsidiaries, own because patents owned by subsidiaries are often considered the property of the parent companies [5], though there is a precedent that a court regards patents assigned to wholly-owned subsidiaries are not considered to be commonly owned by the parent company [68]. They concluded that the key players identified as significant through the main path method for innovation are also considered important players in the EV market [5]. On the other hand, even considering the parent companies of the HPPs in the lithium-ion batteries and permanent magnet motor domains in this thesis, a similar tendency cannot be observed. Therefore, it can be said that the whole picture of the market players in these fields has largely changed between the first half of 2015 and the end of 2023, which are the most recent dates covered by the patent sets of each study. In fact, the supply chain of BEVs for original equipment manufacturers is getting greater complexity due to their increasing demand [69].

Some nodes on Main paths are cited by multiple HPPs, but the assignees of these HPPs do not necessarily match the assignee that owns many HPPs in the domain (Table 4.2). Note that the HPP assignees for multiple domains are only LG Energy Solutions, which has HPPs both in the battery and battery management system domain, and Tesla, which has a patent identified as an HPP both in the battery management system and power electronics).

Table 4.2: Summary of the characteristics of the main paths of each domain/subdomain.

Domain	Subdomain	Number of HPPs /Nodes	Periods of high HPP numbers	Major HPP categories	Number of recent branches	Assignees of 2 or more HPPs - number of HPPs (share of them): standardized current assignee -	Patents on the main paths cited by over 2 HPPs - number of HPPs cited: Node number, patent number, published year, standardized current assignee -
Battery		34/128	mid-1980s to 2023	[constant] diverse - including electrode, electrolyte, cell, and manufacture	9	6 (18%): POLYPLUS BATTERY CO INC 3 (9%): 24M TECH INC 2 (6%): UNOVA 2 (6%): MOLI ENERGY 1990 2 (6%): SION POWER CORP	6: 44335, US5648187A, 1997, SION POWER CORP 5: 43501, US5961672A, 1999, SION POWER CORP 4: 32559, US8048571B2, 2011, POLYPLUS BATTERY CO INC 3: 47471, US4615959A, 1986, SANYO CHEM IND LTD 3: 29073, US8202649B2, 2012, POLYPLUS BATTERY CO INC 3: 24613, US8828580B2, 2014, POLYPLUS BATTERY CO INC
	Lead acid battery	16/33	1976 to 2000	[constant] electrode/electrode carrier, manufacture	3	2 (13%): CALIFORNIA INST OF TECH 2 (13%): ENSCI 2 (13%): GS YUASA INT LTD 2 (13%): CPS TECH HLDG LLC	4: 548, US4507372A, 1985, CALIFORNIA INST OF TECH 3: 564, US4326017A, 1982, HAWKER ENERGY PRODS 3: 404, US6037081A, 2000, GS YUASA INT LTD
	Nickel battery	24/35	1976 to mid-2000s	[constant] electrode/electrode carrier, manufacture, cell	4	6 (25%): PANASONIC CORP 4 (17%): DURACELL U S OPERATIONS INC 2 (8%): WESTINGHOUSE ELECTRIC CORP 2 (8%): YUASA BATTERY	4: 1050, US4985318A, 1991, YUASA BATTERY 3: 875, US6492062B1, 2002, DURACELL U S OPERATIONS INC
	Lithium-ion battery	29/76	mid-1990s to 2023	[constant] electrode, electrolyte, manufacture [recent] nanotechnology	8	4 (14%): AMPRIUS TECH INC 2 (7%): ELECTROVAYA 2 (7%): SION POWER CORP 2 (7%): UMICORE AG & CO KG 2 (7%): GM GLOBAL TECH OPERATIONS LLC	3: 4682, US6964828B2, 2005, UMICORE AG & CO KG 3: 3829, US8450012B2, 2013, AMPRIUS TECH INC
	Solid-state battery	20/46	mid-1990s to 2023	[early] manufacture [middle] electrolyte [later] electrode	3	6 (30%): QUANTUMSCAPE CORP 4 (20%): CYMBET CORP 3 (15%): MARTIN MARIETTA ENERGY SYST 2 (10%): SAPURAST RES	8: 815, US5171413A, 1992, TUFTS UNIV 8: 808, US5512147A, 1996, MARTIN MARIETTA ENERGY SYST 7: 807, US5597660A, 1997, MARTIN MARIETTA ENERGY SYST 6: 790, US5705293A, 1998, LOCKHEED MARTIN ENERGY SYST INC 6: 745, US8268488B2, 2012, SAPURAST RES 5: 613, US9806372B2, 2017, QUANTUMSCAPE CORP 5: 469, US10103405B2, 2018, QUANTUMSCAPE CORP 4: 814, US5338625A, 1994, MARTIN MARIETTA ENERGY SYST 3: 779, US6982132B1, 2006, TRUSTEES OF TUFTS COLLEGE 3: 776, US7194801B2, 2007, CYMBET CORP
Ultra capacitor		9/22	2000 to 2023	[constant] electrode	3	3 (33%): KYOCERA AVX COMPONENTS CORP 2 (22%): NANOTEK INSTR GRP LLC	3: 492, US6187061B1, 2001, RUTGERS THE STATE UNIV

Battery management system		20/49	1990 to 2023	[constant] diverse - including electrical testing and circuit monitoring/indication	5	3 (15%): INT COMPONENTS 2 (10%): REVA ELECTRIC CAR COMPANY PVT 2 (10%): ZOLL MEDICAL CORPORATION	3: 29, US5606242A, 1997, MICROCHIP TECH INC 3: 518, US9000935B2, 2015, ELITE POWER HLDG LLC 3: 1565, US10414285B2, 2019, HYUNDAI MOBIS CO LTD
Electric motor		22/60	1976 to 2023 constantly	[early] rotary current collector [later] magnetic circuit	5	5 (23%): LINEAR LABS 2 (9%): MITSUBISHI ELECTRIC CORP 2 (9%): KOKI HLDG CO LTD	5: 4321, US7898134B1, 2011, SHAW BILL S 5: 4885, US7755244B2, 2010, DANFOSS POWER SOLUTIONS US CO 4: 1896, US9729016B1, 2017, LINEAR LABS 3: 2533, US10263480B2, 2019, LINEAR LABS
	DC motor	33/79	1976 to mid-2000s	[early] motor/generator/ converter stoppers [later] motor starters, synchronous generators	11	3 (9%): GENERAL ELECTRIC CO 3 (9%): SONY CORP 3 (9%): PAPST MOTOREN GMBH & CO KG 2 (6%): KOLLMORGEN CORP 2 (6%): BAN ITSUKI 2 (6%): SHIRAKI MANABU	3: 1060, US4874975A, 1989, QUANTUM CORP
	Induction motor	12/31	1976 to 2000	[early] motor starters [later] manufacture	5	3 (25%): HITACHI LTD	N/A
	Permanent magnet motor	24/34	1976 to 2023 constantly	[constant] magnetic circuit	2	2 (8%): HITACHI LTD 2 (8%): GENERAL ELECTRIC CO 2 (8%): KK TOSHIBA 2 (8%): PANASONIC CORP	4: 1514, US4139790A, 1979, RELIANCE ELECTRIC CO 4: 1424, US4922152A, 1990, SIEMENS ENERGY & AUTOMATION INC 4: 1406, US5097166A, 1992, REULAND ELECTRIC 4: 1357, US5679995A, 1997, SEIKO EPSON CORP 3: 1501, US4358697A, 1982, SIEMENS ALLIS 3: 1411, US5159220A, 1992, GENERAL ELECTRIC CO 3: 1176, US6486581B2, 2002, SANYO DENKI CO LTD
	Switch reluctance motor	13/21	1990 to mid-2010	[constant] synchronous generators	3	3 (23%): EMERSON ELECTRIC CO 2 (15%): PACIFIC SCI CO 2 (15%): BALDOR ELECTRIC COMPANY	5: 127, US4995159A, 1991, PACIFIC SCI CO 3: 125, US5111095A, 1992, BALDOR ELECTRIC COMPANY
Power electronics		9/24	1990 to 2023	[constant] battery circuit arrangements	4	6 (67%): GENERAL ELECTRIC CO	4: 84, US6331365B1, 2001, GENERAL ELECTRIC CO 3: 68, US5710699A, 1998, GENERAL ELECTRIC CO
Heat pump		19/26	1976 to 2023 constantly	[constant] air-treating devices	1	4 (21%): DENSO CORP 3 (16%): HANON SYST 3 (16%): KIA CORP 3 (16%): HYUNDAI MOTOR CO LTD	4: 167, US6047770A, 2000, DENSO CORP 3: 118, US5641016A, 1997, DENSO CORP 3: 160, US5899086A, 1999, CALSONIC KANSEI CORP

Chapter 5

Discussion

This chapter discusses the results of the analysis and the key findings in the context of the research questions from Section 1.3:

1. What is the historical technological improvement trajectory for each component technology of BEVs followed in development? How were technological clusters developed in the trajectory? Which topics and patent holders played important roles in the improvement over time? How were the patent trajectories related to the actual events?
2. Based on the trajectories detected in Question 1, what can be said about the future potential topics of each component technology? Which technologies would have more potential as substitutes? What kind of events may trigger such a replacement? Referencing the trajectories with EV markets and industry trends, what can be suggested as hopeful strategies for the amplification of the technologies?

In the Result Chapter, the historical technological improvement trajectory of each component technology, including the technological clusters, topics, and assignees, is provided based on the main paths analysis. The method can detect the crucial technological innovations within each domain. However, in spite of using the LP so that newer yet influential patents should be included, the identified main paths contain a relatively small number of recent HPPs. This problem is raised by Park and Magee (2017), which suggests that the development of other criteria may provide additional value [9]. Furthermore, the projected patent publication date by the USPTO is 18 months after the earliest filing date claimed by the applicant [70], which means there is a time lag between the publication date and when the actual invention was made.

On the other hand, the BEV field has been rapidly growing, and the number of patent filings related to batteries has been increasing; battery patent filings at the USPTO climbed by 41% from 3,773 in 2010 to 5,319 in 2019 [71]. Therefore, in this section, by comparing the characteristics of the main paths and original patent sets, the discussion about the historical technological improvement trajectory of BEV is deepened.

5.1 Periods and categories with active innovations

While a small number of HPPs tend to be selected from the recent patents in each patent set, the total number of patents in each patent set has increased. Figure 5.1 shows the share of the patents published by year from 1976 to 2023 in the patent set, and Figure 5.2 shows their cumulative share from 1976 in the patent set. Each patent set has a unique size, for example, 49,611 patents in the battery domain and 512 in the ultra capacitor domain, as described in Table 3.1, and these sizes also depend on the method of patent selection, as well as the innovation frequency. Therefore, to make it possible to compare trends with other domains/subdomains, the number of patents published in each year is divided by the total number in the patent set.

As seen in Figure 5.1, though there are fluctuations, all the domains and subdomains have increasing trends. The characteristics have become drastic since 2010, except for the electric motor domain, its subdomains, and the lead acid battery subdomain. 2009 was the year that President Barack Obama announced 2.4 billion dollars in funding to support American ingenuity and America's manufacturers to work producing next-generation electric vehicles [72], and mass BEV sales started in the early 2010s both in the US and globally [73] [74]. Similar activity movements were not observed in the main paths and HPPs. In other words, while the total patent number is sensitive to policy and industry events, the HPPs or main paths are less sensitive, and the critical innovations have not necessarily occurred when the momentum is high. The rapid patent increase since 2010 has been particularly noticeable in the solid-state battery subdomain. As described in the Literature Review Chapter, this battery is stable and performs better. While mass production of solid-state batteries for EVs is pretty limited [14] [75], several major automakers are aiming for commercialization in the late 2020s. It is suggested that this trend is related to the tendency of the increase in the patent number of this subdomain [76].

Figure 5.2 illustrates that the number of patents in the electric motor domain has increased relatively constantly, whereas more than 80% of the patents in the ultra capacitor, battery management system, and power electronics domains have been published after 2010. Breaking down into the subdomains, among the battery subdomains, the new patent publishing has proceeded in the chronological order of the lead acid battery, nickel battery, lithium-ion battery, and solid-state battery, and among the electric motor subdomains, the DC motor and induction motor were developed earlier than other two subdomains. These development characteristics based on the total patent number are consistent with the order of the period of high HPP numbers between domains or subdomains. Furthermore, regarding subdomains, these orders are roughly the same as the development orders written in the Literature Review. Considering those, ultra capacitors, battery management systems, and power electronics, among the components, can gain further importance for BEVs in the near future.

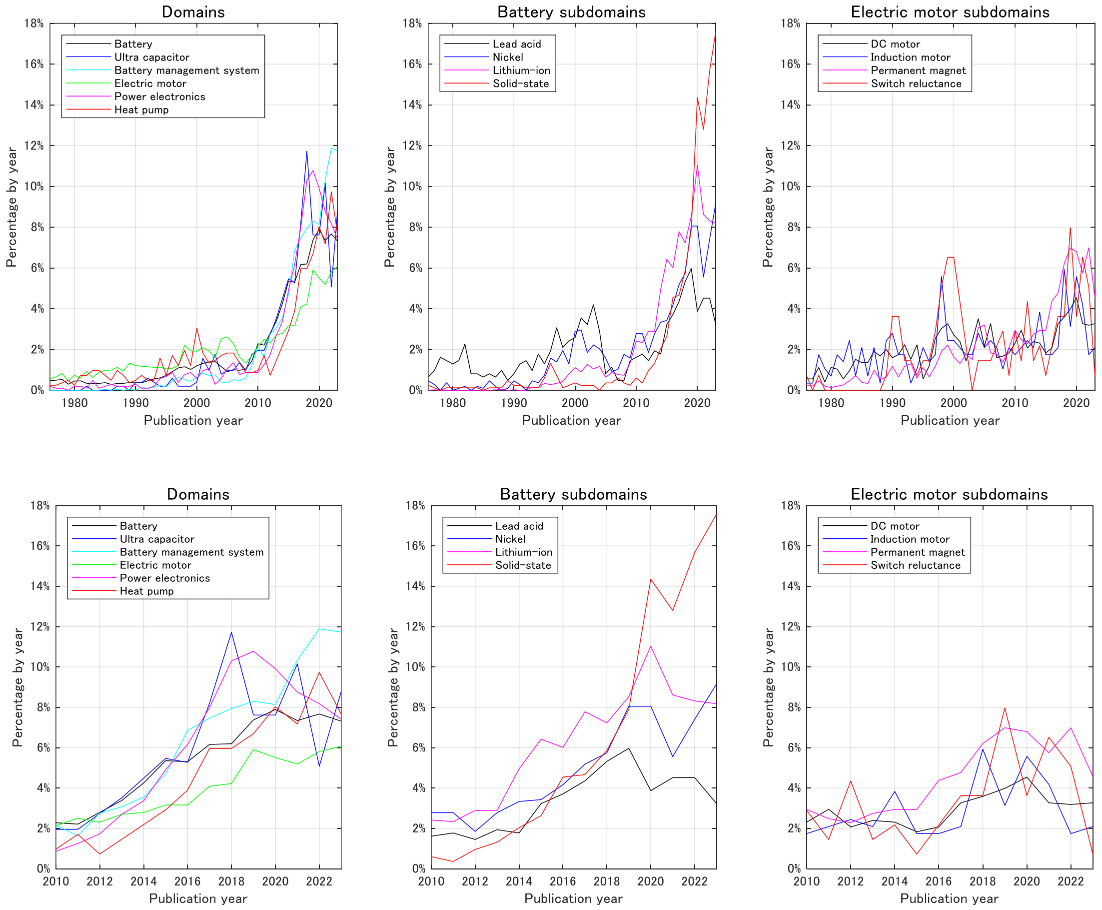

Figure 5.1: Percentage by year within the patent set of each domain/subdomain. Note: The figures are about the six domains, four subdomains in the battery domain, and four subdomains in the electric motor subdomains from the left. The figures in the top row show the shift from 1976 to 2023, and those in the bottom row zoom into the period from 2010 to 2023.

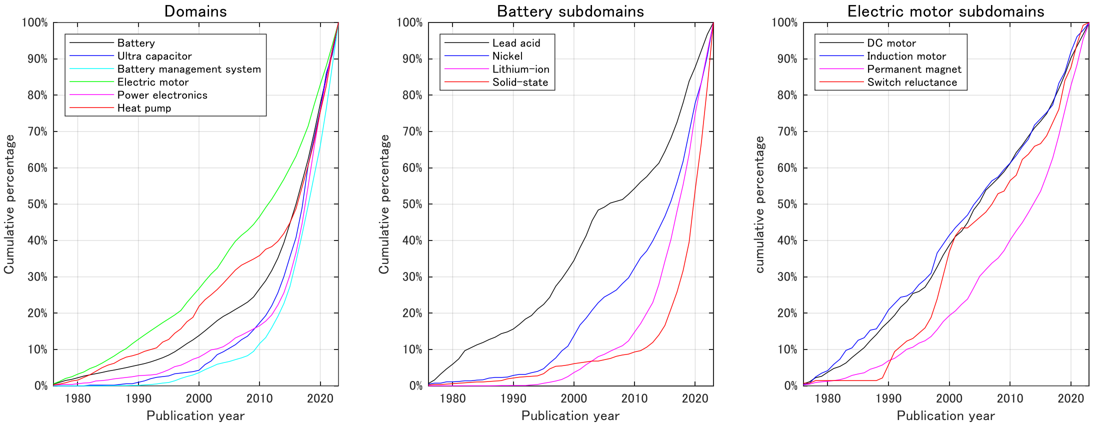

Figure 5.2: Cumulative percentage within the patent set of each domain/subdomain. Note: The figures are about the six domains, four subdomains in the battery domain, and four subdomains in the electric motor subdomains from the left.

Regarding technological categories, as an example, focusing on the solid-state battery subdomain, in recent years, the major HPP technological category has become electrodes since around 2017. When investigating whether the same trend has been seen across the solid-state battery domain from 2017, the category that has the highest share each year has been electrolytes, at around 50%, while the share of electrodes is around 20% (Figure 5.3). That is, the technological category where critical innovations happen at a certain time in a domain is not necessarily the category where the most significant number of innovations occurs in the same period.

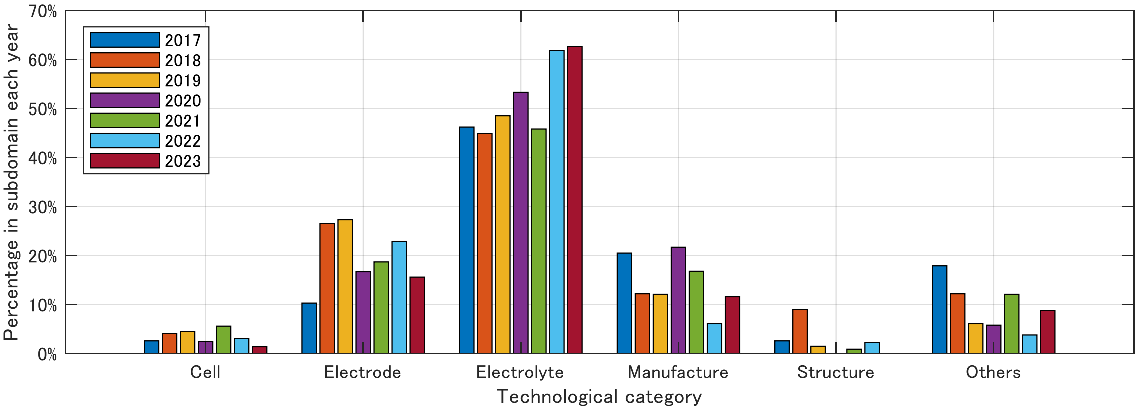

Figure 5.3: Share of each category each year from 2017 to 2023 in the solid-state battery subdomain.

5.2 Patent assignees and top market share companies

As seen in the Result chapter, except for the ultra capacitor, power electronics, and heat pump domains, and the solid-state battery and switch reluctance motor subdomains, over 50% of the HPPs are shared by various assignees in the battery, battery management system, and electric motor domains and the lead acid battery, nickel battery, lithium-ion battery, DC motor, induction motor, and permanent magnet motor subdomains respectively. In addition, players who own HPPs of two or more domains are only two companies. Patents in the automotive industry are typically licensed on vertical levels [77], and because of this, making critical innovations for a wide range of players in this field might not be important. In this section, the characteristics of the assignees of HPPs and patents within the patent sets are compared, considering the market share.

5.2.1 Assignees with a high share of HPPs

First, it is examined whether the assignees with a high share of HPPs in a domain/subdomain, here 25% or more, also have a high share of patents in the domain/subdomain. As a result, all of them are ranked high as the assignees of many patents in the domain/subdomain. However, the share of their patents in the patent set of the same domain/subdomain is 3.9% for QuantumScape in the solid-state battery subdomain, 3.13% for KYOCERA AVX Components Corporation in the ultra capacitor domain, 2.1% for Hitachi in the induction motor subdomain, and 3,2% for General Electric Company in the power electronics domain, and only the share of Panasonic in the nickel battery subdomain exceeded 10%, at 10.5%. In other words, it is suggested that while the entities that have a significant share of important innovations in a field contribute numerous innovations in the field, they do not necessarily dominate the field's overall innovation output.

In contrast, looking at the players who don't own 25% or more HPPs in a domain/subdomain but who own a lot of patents, the assignee with over 10% share, except for Panasonic mentioned above, is only Toyota Motor Corporation applied with the assignee's name of Toyota Jidosha KK: 24.0% in the solid-state battery subdomain and 11.6% in the power electronics domain. Among this domain and subdomain, Toyota Jidosha owns only one HPP in the solid-state battery subdomain. In other words, players who have caused many critical innovations in a field have made relatively many innovations in the field, but they do not necessarily have a high share of the number of innovations. Conversely, even if a company has a high share of the number of innovations, it does not necessarily mean that the company has made critical innovations in technological development. As described in Section 4.9, since the key innovators in each technology are diverting and the supply chain is getting more complex, not only cooperating with the players from the BEV market view but also collaborating with the key innovators in each critical component will also be critical.

Nevertheless, solid-state batteries are said to be a technology that attracts attention for future BEVs [78], and the patents of Toyota Jidosha in the solid-state battery subdomain were all published in 2012 or later. On the other hand, more than half of HPPs in this subdomain were published before 2012. Considering these characteristics, the reason why Toyota Jidosha only has one HPP in this subdomain can be explained by the shortcoming of this main paths method in which recent innovations are not sufficiently picked up as HPPs, and Toyota Jidosha is fully expected to have already produced, or to produce, critical innovations in the development of solid-state batteries in the future.

5.2.2 Market competitive players and their patents

Second, while the HPP assignees for multiple domains are only LG Energy

Solutions and Tesla, which own HPPs from two domains, as described in Section 4.9, cross-sectoral patent holders are examined to evaluate the relationship between the competitiveness in the BEV markets and patent ownership trends.

GM Global Technology Operations, Ford Global Technologies, Hyundai Motor, Robert Bosch GmbH, Kia, and Honda Motor hold at least one patent in each of the six domains. It is assumed that the patents of a subsidiary are owned by its parent company and given the right to other subsidiaries under the parent company as well. For example, Chevrolet is assumed to be usable for the patents held by GM Global Technology Operations [79]. Then, all these companies, except for Robert Bosch GmbH and Honda Motor, are ranked within the Top 10 of the BEV market share in the U.S. (Table 5.1) [80]. The rest of the companies within the Top 10 in U.S. sales, Tesla, Rivian, Bayerische Motoren Werke (BMW), Mercedes-Benz, Volkswagen, and Audi, have at least one patent in five domains except for the ultracapacitor domain. Those companies within the Top 10 in U.S. sales also have a certain amount of U.S. patents related to BEVs.

On the other hand, regarding the companies ranked within the global Top 10 but not in the U.S, whereas BYD holds patents except for the ultra capacitor domain, Guangzhou Automobile Group Co., Ltd (GAC) Aion has patents only in the battery and battery management system domains and no patents owned by Shanghai Automotive Industry Corporation (SAIC)-GM-Wuling or Morris Garages (MG) are hit in any patent sets.

What can be said from these facts is as follows. First, in order to gain market share in the U.S., it is essential to obtain U.S. granted patents for each important component technological field, though this is not sufficient to enhance competitiveness. Second, among the six domains analyzed in this thesis, making innovations of ultra capacitors is less critical to gaining market share compared to others. Third, unless a company has a top BEV market share in the U.S., even if the company has a top global market share, it does not necessarily place importance on acquiring patents in the U.S. This is probably caused because the BEV market size is currently many times larger in China than in the U.S. and because more EVs are produced in China than the number of EVs registered there [81]. This trend would likely change depending on the target market countries and supply chain strategies.

Table 5.1: BEV market share of global sales and sales in the U.S. by company. Note: The global sales are based on the unit sales in the world in 2023, reported by TrendForce (2024) [82]. The sales in the U.S. are based on the unit sales in the U.S. in 2023, reported by Cox Automotive (2024) [80].

Rank	Global sales		Sales in the U.S.	
1	Tesla (US)	19.9%	Tesla (US)	55.1%
2	BYD (China)	17.1%	Ford (US)	6.1%
3	GAC Aion (China)	5.2%	Chevrolet (US)	5.3%
4	SAIC-GM-Wuling (China)	4.9%	Hyundai (Korea)	4.8%
5	Volkswagen (Germany)	4.6%	Rivian (US)	4.2%
6	BMW (Germany)	3.6%	BMW (Germany)	3.8%
7	Hyundai (Korea)	2.9%	Mercedes-Benz (Germany)	3.4%
8	Mercedes-Benz (Germany)	2.6%	Volkswagen (Germany)	3.2%
9	MG (China)	2.3%	Kia (Korea)	2.5%
10	Kia (Korea)	2.0%	Audi (Germany)	2.1%

5.3 Limitations of this study

Certain limitations should be considered when reviewing this analysis. The first is the limitation of the analyzed patent sets with the huge number of patents. Due to the volume of the patents, the patent sets are established by searching keywords and classes, but a certain number of patents that are not related to the specific technology are included by this method. They also include patents that are properly categorized but not used for BEVs. Furthermore, the technological categories are classified based on the application domains provided by patsnap, but the classification is not necessarily suitable for referring to trends in technological categories.

The second limitation is using only the U.S. patents for the BEV analysis. While there are advantages to using them as described in Section 3.1, they do not cover the trends of the BEV global market under the circumstances that the primary market of BEVs is not the U.S. and that the supply chains for component technologies are not formed mainly in the U.S., as mentioned in Section 5.2.

The third is the limitation of analyzing technology trends with only patents. In addition to the lack of information on quantitative performance metrics, companies protect their intellectual properties with both patents and trade secrets [83], which means not all innovations are published as patents. The balance of these two strategies depends on the company and is generally not disclosed in detail. Furthermore, patents are not directly representative of the markets or products, and the value of each patent is not the same from the perspective of succeeding in the markets or products.

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Chapter 6

Conclusions

This thesis demonstrates the value of detecting the technological development trajectories of the component technologies in BEVs based on analyzing the main paths in considering future trends and strategies. It begins by describing why BEVs have been getting more attention and why improving their component technologies is essential in the Introduction Chapter. The Literature Review Chapter provides relevant context for the key technologies and their challenges related to BEVs, the concept of technology infusion, and previous BEV development analysis using patent data. The patent data and methods used for the study are laid out in the Data and Methods Chapter, and the results are displayed in the following Results Chapter. Finally, these results are discussed, and the research questions are examined for insights from the study in the Discussion Chapter. This chapter will provide conclusions for the analysis and outline opportunities for future work.

First, regarding the innovations published as patents, critical innovations do not necessarily occur when many innovations occur. In addition, as observed in the recent solid-state battery subdomain, a technological category that is intensively worked on may not result in essential innovations in the domain/subdomain. According to the main path analysis, important innovations have been made constantly related to electrodes, electrolytes, cells, and manufacturing in the battery field, electrical testing and circuit monitoring/induction in the battery management system domain, battery circuit arrangements in power electronics technology, and air-treating devices in the heat pump domain. These trends are stable and suggested to continue. On the other hand, critical innovations occurred relatively recently and intensively regarding the nanotechnology of lithium-ion batteries, electrodes of solid-state batteries, and magnetic circuits of electric motors. It is confirmed from references that these categories or subdomains have been attracting more attention in recent years due to their high potential to improve performance. Therefore, these trends are expected to continue in the near term. Since it is challenging to predict future trends, these findings can be worthwhile for companies and researchers when choosing focuses for research and development toward further performance improvement. They may also offer additional insights for institutions that invest in or subsidize research and development in the BEV field.

Second, in order to gain market share for BEVs in the US, it is necessary to obtain U.S. patents for the major component technologies of BEVs, specifically batteries, battery management systems, electric motors, power electronics, and heat pumps. On the other hand, this is not the case to succeed in the global markets as the U.S. is not currently the primary market for BEVs. In addition, based on the main path analysis, companies that have acquired a high market share of BEVs in the U.S. do not necessarily have made critical innovations in the development of each component technology. This trend is different from nearly 10 years ago when key players in the market were making key innovations. Nowadays, significant innovations in key technologies, such as batteries, battery management systems, electric motors, and heat pumps, are made by a wide variety of players, including but not limited to automotive companies. Up until now, patents in the automotive industry are typically held on verticals, and they have actually gained market share in the U.S. However, from now on, it can become increasingly important for BEV companies to make supply chain strategies from multiple angles, such as not only developing technology within their own group but also incorporating emerging start-ups with critical innovations into their own companies or entering into horizontal contracts with companies that possess emerging technologies. In addition, in the technology fields with diverse players, key players may be quickly replaced by competitive players, and even enterprises that are currently considered less advanced can have the potential to win in the near future.

This study can be a building block for future work in this field. This thesis analyzed U.S. patents, but applying the same main path method to patents in other countries, including China, which has the largest BEV market, will identify regional differences and suggestions about strategies to gain global market share. In addition, comparing the main paths identified in this thesis with future trajectories in the real world may provide concrete insights into how to predict future trends based on the main paths. Furthermore, the main path analysis is not the only method to investigate technological developments using patents, and furthermore, given the limitation of analyzing technology trends with only patents, a combination of other methods or interviews will enhance the certainty. The BEV markets are rapidly growing, and many technologies are being developed; therefore, these are worth studying as future work.

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Appendix A

Patents on the main paths of each domain/subdomain

This appendix includes the patent lists on the main paths of each domain and subdomain following the battery domain shown in Table 4.1.

Table A.1: Patents on the main paths of the lead acid subdomain. Note: 16 HPPs out of 33 Nodes. The list is in order of publication year. White cells are for HPPs, and gray cells are for LPPs. The numbers in the Node column are procedurally assigned different numbers to all patents within a domain/subdomain, and they do not affect the results or have meanings. The column of the Number shows the patent number assigned by the USPTO. The year is the publication year of each patent. The assignee's names in the Current assignee column follow the Standardized Current Assignee provided by patsnap. From Table A.2 to Table A.13 follow the same rules.

Node	Number	Year	Current assignee
616	US3973991A	1976	NL IND INC
612	US3989539A	1976	VARTA BATTERIES LTD
614	US4037031A	1977	IMPERIAL METAL IND (KYNOCH) LTD
563	US4320183A	1982	EXIDE
564	US4326017A	1982	HAWKER ENERGY PRODS
558	US4411969A	1983	KOEHLER MFG
548	US4507372A	1985	CALIFORNIA INST OF TECH
404	US6037081A	2000	GS YUASA INT LTD
413	US6190799B1	2001	ENSCI
345	US6511771B1	2003	ENSCI
328	US6777131B1	2004	ENSCI
340	US6699620B2	2004	JOHNSON CONTROLS TECH CO
325	US7083876B2	2006	SHIN KOBE ELECTRIC MASCH CO LTD
270	US8017273B2	2011	UT BATTELLE LLC

527	US4873161A	1989	CALIFORNIA INST OF TECH 1201 E CALIFORNIA BOULEVARD PASADENA CA 91125 A CA
522	US5156935A	1992	GS YUASA CORP
493	US5334464A	1994	BIPOLAR POWER CORP
475	US5549990A	1996	ENSCI
473	US5547783A	1996	GS YUASA INT LTD
464	US5667917A	1997	IDAHO RESARCH FOUNDATION INC
460	US5601953A	1997	VENTURE ENTERPRISES
439	US5762654A	1998	EXIDE TECHNOLOGIES LLC
445	US5895732A	1999	ENSCI
428	US5948566A	1999	EXIDE
209	US9281520B2	2016	CABOT CORP
213	US9812703B2	2017	COMMONWEALTH SCI & IND RES ORG | THE FURUKAWA BATTERY CO LTD
178	US9748578B2	2017	CPS TECH HLDG LLC
173	US9991487B2	2018	DARAMIC LLC
80	US10985380B2	2021	CPS TECH HLDG LLC
59	US11302991B2	2022	DARAMIC LLC
47	US11289771B2	2022	HOLLINGSWORTH VOSE
9	US11824204B2	2023	CPS TECH HLDG LLC
2	US11804634B2	2023	HOLLINGSWORTH VOSE

Table A.2: Patents on the main paths of the nickel battery subdomain. Note: 24 HPPs out of 35 Nodes.

Node	Number	Year	Current assignee
1080	US3951686A	1976	VARTA BATTERIE AG
1078	US3941614A	1976	WESTINGHOUSE ELECTRIC CORP
1077	US4016091A	1977	WESTINGHOUSE ELECTRIC CORP
980	US6045771A	2000	TODA IND
912	US6241959B1	2001	SAMSUNG ELECTRONICS DEVICES CO LTD
875	US6492062B1	2002	DURACELL U S OPERATIONS INC

1065	US4481128A	1984	US SEC THE DEPT OF ENERGY THE
1054	US4844999A	1989	YUASA BATTERY
1055	US4935318A	1990	PANASONIC CORP
1049	US4980080A	1990	SAFT GRP SA
1050	US4985318A	1991	YUASA BATTERY
1045	US5200282A	1993	YUASA CORP TAKATSUKI OSAKA JP
1026	US5466543A	1995	PANASONIC CORP
1035	US5490320A	1996	PANASONIC CORP
1022	US5506076A	1996	TOSHIBA BATTERY
1005	US5660952A	1997	FDK CORP
997	US5626635A	1997	GK BRIDGE 1
1043	US5700596A	1997	PANASONIC CORP
981	US5804334A	1998	PANASONIC CORP
931	US6114063A	2000	PANASONIC CORP
954	US6013390A	2000	PANASONIC CORP
849	US6773852B2	2004	SAMSUNG SDI CO LTD
776	US7273680B2	2007	DURACELL U S OPERATIONS INC
722	US7939200B2	2011	PANASONIC CORP | OSAKA CITY UNIV
667	US8048558B2	2011	ZINCFIVE POWER INC
567	US8703336B2	2014	DURACELL U S OPERATIONS INC
556	US8715859B2	2014	KK TOSHIBA
516	US8765304B2	2014	KK TOSHIBA
756	US8703330B2	2014	ZINCFIVE POWER INC
568	US9570741B2	2017	DURACELL U S OPERATIONS INC
418	US9543576B2	2017	DURACELL U S OPERATIONS INC
300	US9819012B2	2017	DURACELL U S OPERATIONS INC
299	US9859558B2	2018	DURACELL U S OPERATIONS INC
138	US11081696B2	2021	DURACELL U S OPERATIONS INC
31	US11799082B2	2023	DURACELL U S OPERATIONS INC

Table A.3: Patents on the main paths of the lithium-ion battery subdomain. Note: 29 HPPs out of 76 Nodes.

Node	Number	Year	Current assignee
5050	US4049887A	1977	EXXON RES & ENG CO
5048	US4684590A	1987	ELTRON RES INC
391	US10714753B1	2020	ADVANO INC
851	US10833361B2	2020	POLYPLUS BATTERY CO INC

5044	US5196279A	1993	VALENCE TECH INC	821	US10840546B2	2020	POLYPLUS BATTERY CO INC
5028	US5312611A	1994	KK TOSHIBA	474	US10608256B1	2020	ADVANO INC
5024	US5314765A	1994	MARTIN MARIETTA ENERGY SYST	819	US10833521B2	2020	STOREDOT
5011	US5437692A	1995	ELECTROVAYA	1009	US10601070B2	2020	STOREDOT
5012	US5518842A	1996	MOLI ENERGY 1990	732	US10581065B1	2020	STOREDOT
4982	US5648187A	1997	SION POWER CORP	936	US10811675B2	2020	AMPRIUS TECH INC
5022	US5824434A	1998	CANON KK	1109	US10673250B2	2020	CF TRAVERSE LLC
4959	US5753387A	1998	KK TOSHIBA	1100	US10665858B2	2020	CF TRAVERSE LLC
4914	US6007945A	1999	ELECTROVAYA	1110	US10727481B2	2020	CF TRAVERSE LLC
4937	US5908715A	1999	HUGHES ELECTRONICS CORP	1101	US10727482B2	2020	CF TRAVERSE LLC
4928	US5961672A	1999	SION POWER CORP	749	US10549650B2	2020	STOREDOT
4981	US5882218A	1999	MOLI ENERGY 1990	900	US11069885B2	2021	UNIFRAX I LLC
4921	US6270925B1	2001	TODA IND	690	US11205796B2	2021	STOREDOT
4630	US6761744B1	2004	QUALLION	515	US10910671B2	2021	STOREDOT
4636	US6680143B2	2004	UCHICAGO ARGONNE LLC	858	US11069918B2	2021	STOREDOT
4751	US6749648B1	2004	NANOGRAM	719	US10916811B2	2021	STOREDOT
4682	US6964828B2	2005	UMICORE AG & CO KG	563	US10991946B2	2021	GM GLOBAL TECH OPERATIONS LLC
4438	US7078128B2	2006	UMICORE AG & CO KG	352	US10978702B2	2021	CF TRAVERSE LLC
4547	US7094499B1	2006	NASA	311	US11127948B2	2021	CF TRAVERSE LLC
4454	US7563541B2	2009	MEDTRONIC INC	310	US11152612B2	2021	CF TRAVERSE LLC
4535	US7498100B2	2009	JOHNSON MATTHEY PLC	461	US11152602B2	2021	STOREDOT
4162	US7745047B2	2010	SAMSUNG ELECTRONICS CO LTD	438	US11165106B2	2021	STOREDOT
4371	US7682750B2	2010	HON HAI PRECISION IND CO LTD	440	US11088402B2	2021	STOREDOT

4282	US7906238B2	2011	SICONA BATTERY TECH PTY LTD	691	US11251430B2	2022	THE RES FOUND OF STATE UNIV OF NEW YORK
3829	US8450012B2	2013	AMPRIUS TECH INC	555	US11394046B2	2022	STOREDOT
3626	US8658295B2	2014	GM GLOBAL TECH OPERATIONS LLC	338	US11289701B2	2022	AMPRIUS TECH INC
2897	US9362549B2	2016	KANSAS STATE UNIV RES FOUND | CF TRAVERSE LLC	480	US11233234B2	2022	CF TRAVERSE LLC
1795	US10164245B2	2018	GM GLOBAL TECH OPERATIONS LLC	94	US11652201B2	2023	UNIFRAX I LLC
1635	US10454101B2	2019	STOREDOT	630	US11831012B2	2023	STOREDOT
1310	US10505181B2	2019	STOREDOT	66	US11855279B2	2023	AMPRIUS TECH INC
1247	US10199677B2	2019	STOREDOT	403	US11575156B2	2023	STOREDOT
2253	US10290871B2	2019	ZENLABS ENERGY INC	237	US11646445B2	2023	POLYPLUS BATTERY CO INC
1108	US10461324B2	2019	CF TRAVERSE LLC	236	US11646444B2	2023	POLYPLUS BATTERY CO INC
1171	US10615463B2	2020	MEDTRONIC INC	565	US11749834B2	2023	POLYPLUS BATTERY CO INC
1186	US10707484B2	2020	AMPRIUS TECH INC	162	US11637324B2	2023	GM GLOBAL TECH OPERATIONS LLC
1202	US10637065B2	2020	APAQ TECH	499	US11560062B2	2023	STOREDOT

Table A.4: Patents on the main paths of the solid-state battery subdomain. Note: 20 HPPs out of 46 Nodes.

Node	Number	Year	Current assignee	Node	Number	Year	Current assignee
824	US4832463A	1989	TUFTS UNIV	473	US10622680B2	2020	INT BUSINESS MASCH CORP
815	US5171413A	1992	TUFTS UNIV	264	US10581115B2	2020	CORNING INC
814	US5338625A	1994	MARTIN MARIETTA ENERGY SYST	476	US10581109B2	2020	INT BUSINESS MASCH CORP
808	US5512147A	1996	MARTIN MARIETTA ENERGY SYST	641	US10777839B2	2020	INFINEON TECH AG

807	US5597660A	1997	MARTIN MARIETTA ENERGY SYST
790	US5705293A	1998	LOCKHEED MARTIN ENERGY SYST INC
779	US6982132B1	2006	TRUSTEES OF TUFTS COLLEGE
776	US7194801B2	2007	CYMBET CORP
765	US7157187B2	2007	CYMBET CORP
766	US7274118B2	2007	CYMBET CORP
755	US7389580B2	2008	CYMBET CORP
759	US7959769B2	2011	SAPURAST RES
739	US8304115B1	2012	POLYMER INNOVATIONS
745	US8268488B2	2012	SAPURAST RES
616	US9455437B2	2016	INTERMOLECULAR
657	US9318774B2	2016	GOOGLE LLC
613	US9806372B2	2017	QUANTUMSCAPE CORP
638	US9748582B2	2017	GOOGLE LLC
469	US10103405B2	2018	QUANTUMSCAPE CORP
648	US9887414B2	2018	DEMARAY
640	US9859542B2	2018	INFINEON TECH AG
548	US10084207B2	2018	GOOGLE LLC
600	US10008739B2	2018	KLA CORP
416	US10629957B2	2020	INT BUSINESS MASCH CORP
418	US10644355B2	2020	INT BUSINESS MASCH CORP
417	US10644356B2	2020	INT BUSINESS MASCH CORP
419	US10673097B2	2020	INT BUSINESS MASCH CORP
642	US10622666B2	2020	UNIV OF MARYLAND
227	US11139503B2	2021	QUANTUMSCAPE CORP
283	US11171357B2	2021	QUANTUMSCAPE CORP
85	US11171358B2	2021	QUANTUMSCAPE CORP
391	US11056722B2	2021	INT BUSINESS MASCH CORP
445	US11158880B2	2021	QUANTUMSCAPE CORP
260	US11355779B2	2022	QUANTUMSCAPE CORP
248	US11367896B2	2022	QUANTUMSCAPE CORP
148	US11417870B2	2022	FORSCHUNGSZENTRUM JULICH GMBH
256	US11424479B2	2022	TOYOTA JIDOSHA KK
152	US11258095B2	2022	TAIYO YUDEN KK
36	US11575153B2	2023	QUANTUMSCAPE CORP
17	US11600857B2	2023	QUANTUMSCAPE CORP
9	US11658338B2	2023	QUANTUMSCAPE CORP

Table A.5: Patents on the main paths of the ultra capacitor domain. Note: 9 HPPs out of 22 Nodes.

Node	Number	Year	Current assignee	Node	Number	Year	Current assignee
501	US5811205A	1998	SAFT GRP SA	320	US9145760B2	2015	HALLIBURTON ENERGY SERVICES INC

492	US6187061B1	2001	RUTGERS THE STATE UNIV	319	US9169719B2	2015	HALLIBURTON ENERGY SERVICES INC
478	US6510043B1	2003	LUXON ENERGY DEVICES CORP	273	US9437372B1	2016	NANOTEK INSTR GRP LLC
472	US6762926B1	2004	GAINIA INTELLECTUAL ASSET SERVICES	281	US9774201B2	2017	ZAPGO LTD
65	US6944009B2	2005	MOLEX INC	8	US11195656B2	2021	KYOCERA AVX COMPONENTS CORP
63	US7248458B2	2007	AMERICAN TECH CERAMICS CORP	150	US11114868B2	2021	BBY SOLUTIONS
462	US7312976B2	2007	UNIVERSAL SUPERCAPACITORS LLC	15	US10943735B2	2021	KYOCERA AVX COMPONENTS CORP
457	US7623340B1	2009	SAMSUNG ELECTRONICS CO LTD | NANOTEK INSTR GRP LLC	11	US11361907B2	2022	KYOCERA AVX COMPONENTS CORP
456	US7881042B2	2011	WAINWRIGHT D WALKER	2	US11830676B2	2023	KYOCERA AVX COMPONENTS CORP
51	US8446705B2	2013	KYOCERA AVX COMPONENTS CORP	1	US11664169B2	2023	KYOCERA AVX COMPONENTS CORP
340	US8881832B2	2014	HALLIBURTON ENERGY SERVICES INC	3	US11728092B2	2023	KYOCERA AVX COMPONENTS CORP

Table A.6: Patents on the main paths of the battery management system domain. Note: 20 HPPs out of 49 Nodes.

Node	Number	Year	Current assignee	Node	Number	Year	Current assignee
5	US5027294A	1991	NEC CORP	666	US9069044B2	2015	ROBERT BOSCH GMBH | SAMSUNG SDI CO LTD
13	US5254928A	1993	APPLE INC	704	US9440550B2	2016	PHILADELPHIA SCI
45	US5545967A	1996	PAS CAPS	624	US9653759B2	2017	THE BOEING CO

34	US5565759A	1996	MICRON TECH INC	1149	US9819059B2	2017	SAMSUNG SDI CO LTD
43	US5703464A	1997	REVA ELECTRIC CAR COMPANY PVT	1236	US9533547B2	2017	THUNDER POWER NEW ENERGY VEHICLE DEV CO LTD
66	US5701068A	1997	HORIZON BATTERIES	1382	US9707822B2	2017	THUNDER POWER NEW ENERGY VEHICLE DEV CO LTD
29	US5606242A	1997	MICROCHIP TECH INC	1565	US10414285B2	2019	HYUNDAI MOBIS CO LTD
79	US5929601A	1999	ZOLL MEDICAL CORPORATION	1523	US10237830B1	2019	GOOGLE LLC
77	US6031354A	2000	AIMS SYST	1478	US10272736B2	2019	THUNDER POWER NEW ENERGY VEHICLE DEV CO LTD
106	US6184656B1	2001	REVA ELECTRIC CAR COMPANY PVT	1613	US10406888B2	2019	THUNDER POWER NEW ENERGY VEHICLE DEV CO LTD
107	US6169387B1	2001	ZOLL MEDICAL CORPORATION	1248	US10527678B2	2020	SAMSUNG ELECTRONICS CO LTD
172	US6856922B1	2005	ANALOG DEVICES INC	1629	US11072242B2	2021	LG ENERGY SOLUTION LTD
170	US6983212B2	2006	SCHNEIDER ELECTRIC IT CORP	1917	US11165270B2	2021	MICROSOFT TECH LICENSING LLC
211	US7349816B2	2008	ASKALITY LLC	2188	US10938221B1	2021	INT COMPONENTS
305	US7634369B2	2009	SAMSUNG SDI CO LTD	2190	US10944278B1	2021	INT COMPONENTS
266	US7710073B2	2010	HITACHI ASTEMO LTD	1882	US10945213B2	2021	GOOGLE LLC
218	US7728552B2	2010	AMERICA POWER CONVERSION CORP	2400	US11245268B1	2022	INT COMPONENTS
449	US8264201B2	2012	ROBERT BOSCH GMBH | SAMSUNG SDI CO LTD	2367	US11581588B2	2023	HUAWEI DIGITAL POWER TECH CO LTD
497	US8219333B2	2012	O2 MICRO INT LTD	2363	US11735782B2	2023	UTAH STATE UNIVERSITY

442	US8341449B2	2012	LG ENERGY SOLUTION LTD	2446	US11705741B2	2023	INT COMPONENTS
446	US8336319B2	2012	TESLA INC	2199	US11735930B2	2023	LG ENERGY SOLUTION LTD
393	US8825417B1	2014	THE BOEING CO	2419	US11688889B2	2023	BETA AIR LLC
518	US9000935B2	2015	ELITE POWER HLDG LLC	2502	US11840158B2	2023	WING AVIATION LLC
916	US9056556B1	2015	ELWHA LLC	2237	US11565605B2	2023	WING AVIATION LLC

Table A.7: Patents on the main paths of the electric motor domain. Note: 22 HPPs out of 60 Nodes.

Node	Number	Year	Current assignee	Node	Number	Year	Current assignee
9068	US3979615A	1976	AMP INC	6057	US6661134B2	2003	CALSONIC KANSEI CORP
8911	US4071793A	1978	THE BLACK & DECKER MFG CO	6192	US6577030B2	2003	MITSUBISHI ELECTRIC CORP
8906	US4164690A	1979	PAPST MOTOREN GMBH & CO KG	5931	US6707185B2	2004	MITSUBISHI ELECTRIC CORP
8838	US4211963A	1980	PAPST MOTOREN GMBH & CO KG	5467	US7021418B2	2006	MITSUBISHI ELECTRIC CORP
8857	US4227104A	1980	EATON STAMPING	5544	US7067950B2	2006	BERG & BERG ENTERPRISES
8697	US4360751A	1982	KOLLMORGEN CORP	5457	US7462965B2	2008	MATSUSHITA DENKO KK
8636	US4409505A	1983	POLAROID CORP	4885	US7755244B2	2010	DANFOSS POWER SOLUTIONS US CO
8576	US4459087A	1984	ECIA - EQUIPS & COMPOSANTS POUR LIND AUTOMOBLIE	4550	US7932651B2	2011	MITSUBISHI ELECTRIC CORP
8473	US4556828A	1985	LOCKHEED MARTIN CORP	5442	US7971650B2	2011	OILFIELD EQUIP DEVMENT CENT
8415	US4593220A	1986	BLACK & DECKER INC	4661	US8084901B2	2011	KOKI HLDG CO LTD
8401	US4585964A	1986	EMERSON ELECTRIC CO	4321	US7898134B1	2011	SHAW BILL S

8120	US4841204A	1989	STUDER PHILIP A
8085	US4831297A	1989	WESTINGHOUSE ELECTRIC CORP | CURTISS WRIGHT ELECTRO MECHANICAL
8108	US4845396A	1989	CAPSONIC GROUP
8116	US4801833A	1989	EATON TENNESSEE
7927	US4931681A	1990	SPAL AUTOMOTIVE
7790	US5101128A	1992	CURTISS WRIGHT ELECTRO MECHANICAL | WESTINGHOUSE ELECTRIC CORP
7784	US5159221A	1992	MITSUBA CORP
7659	US5258697A	1993	SCHOEPE ADOLF | VARELUX MOTOR
7558	US5268607A	1993	PARKER INTANGIBLES LLC | BANKBOSTON N A AS AGENT
7971	US5280210A	1994	KRESS ELEKTRIK & ELEKTROMOTORENFAB
7457	US5440186A	1995	MOTORS ACQUISITION | JOHNSON ELECTRIC AUTOMOTIVE
7451	US5514923A	1996	GOSSLER SCOTT E | MURRAY EUGENE R
7364	US5627423A	1997	ASKOLL
7183	US5796198A	1998	MITSUBA CORP
6851	US5923111A	1999	GOULDS PUMPS
6830	US6107716A	2000	TRW LUCAS VARITY ELECTRIC STEERING
6466	US6297572B1	2001	CALSONIC KANSEI CORP
6470	US6183208B1	2001	CORNELL PUMP CO LLC
4256	US8643231B2	2014	MOOG INC
3827	US8646568B2	2014	DENSO CORP
4320	US8816544B2	2014	KOKI HLDG CO LTD
3229	US9314900B2	2016	BLACK & DECKER INC
1896	US9729016B1	2017	LINEAR LABS
2422	US10122248B2	2018	FAGOR SCOOP LTDA
2533	US10263480B2	2019	LINEAR LABS
1829	US10272558B2	2019	BLACK & DECKER INC
2173	US10404136B2	2019	BLACK & DECKER INC
2434	US10193417B2	2019	BLACK & DECKER INC
2287	US10284047B2	2019	BLUFFTON MOTOR WORKS
2172	US10226849B2	2019	BLACK & DECKER INC
1565	US10447103B2	2019	LINEAR LABS
2398	US10476362B2	2019	LINEAR LABS
1553	US10530221B2	2020	IND TECH RES INST
1359	US10927802B2	2021	US WELL SERVICS LLC
397	US11277062B2	2022	LINEAR LABS
69	US11777386B2	2023	LINEAR LABS

6326	US6259233B1	2001	BERG & BERG ENTERPRISES	244	US11674484B2	2023	US WELL SERVICS LLC

Table A.8: Patents on the main paths of the DC motor subdomain. Note: 33 HPPs out of 79 Nodes.

Node	Number	Year	Current assignee	Node	Number	Year	Current assignee
1250	US3959705A	1976	SALIHI JALAL TAWFIQ	814	US5952760A	1999	SEIKO EPSON CORP
1255	US4005347A	1977	GENERAL ELECTRIC CO	895	US5909072A	1999	PAPST MOTOREN GMBH & CO KG
1226	US4169990A	1979	GENERAL ELECTRIC CO	781	US6034458A	2000	SEIKO EPSON CORP
1215	US4228384A	1980	KOLLMORGEN CORP	745	US6194799B1	2001	MAGNETIC MOTORS
1217	US4217508A	1980	SONY CORP	783	US6304045B1	2001	SIEMENS CANADA LTD
1188	USRE30761E1	1981	BAN ITSUKI | SHIRAKI MANABU	737	US6307344B1	2001	VWG LLC
1176	US4404485A	1983	BAN ITSUKI | SHIRAKI MANABU | EGAMI KAZUHITO	719	US6456024B1	2002	EBM PAPST ST GEORGEN & - | TRILLIUM HLDG L L C
1174	US4405885A	1983	MATSUSHITA ELECTRONICS CORP	721	US6563245B1	2003	AISIN SEIKI KK
1192	US4396875A	1983	SONY CORP	717	US6538403B2	2003	BLACK & DECKER INC
1200	US4369383A	1983	KOLLMORGEN CORP	647	US6710504B2	2004	JAPAN SERVO CO LTD
1161	US4459087A	1984	ECIA - EQUIPS & COMPOSANTS POUR LIND AUTOMOBLIE	620	US6809457B1	2004	SUNONWEALTH ELECTRIC MACHINE IND
1155	US4494028A	1985	COMAIR ROTRON	725	US6710581B1	2004	I S MOTOR KOREA
1139	US4553075A	1985	COMAIR ROTRON	723	US6891304B1	2005	QUEBEC METAL POWDERS
1165	US4528485A	1985	GENERAL ELECTRIC CO	610	US7218027B2	2007	TEAM ORION EURO
1121	US4600864A	1986	SANYO ELECTRIC CO LTD	561	US7239060B2	2007	QUEBEC METAL POWDERS
1122	US4563622A	1986	COMAIR ROTRON	537	US7564203B2	2009	SOMFY ACTIVITES SA

1132	US4564778A	1986	AUPAC	572	US7635039B2	2009	MITSUBISHI HEAVY IND LTD
1119	US4618806A	1986	COMAIR ROTRON	534	US7586660B2	2009	RICOH KK
1095	US4698538A	1987	AUPAC	555	US7755232B2	2010	ROBERT BOSCH GMBH
1051	US4851731A	1989	SONY CORP	455	US7821170B2	2010	JOHNSON ELECTRIC SA
1049	US4876472A	1989	SHICOH ENG | M GOTTLIEB ASSOC	504	US7884580B2	2011	LEE OAK JAE
1060	US4874975A	1989	QUANTUM CORP	474	US8049376B2	2011	FORD GLOBAL TECH LLC | VISTEON GLOBAL TECH INC
1115	US4882511A	1989	PAPST MOTOREN GMBH & CO KG	394	US8217548B2	2012	JOHNSON ELECTRIC SA
1047	US4891567A	1990	MINEBEAMITSUMI INC	480	US8638014B2	2014	RESMED MOTOR TECH
1088	US4937485A	1990	HHK	325	US8933656B2	2015	ZHONGSHAN BROAD OCEAN
1011	US5041749A	1991	ISKRA ELECTROMORJI	179	US9774229B1	2017	MILWAUKEE ELECTRIC TOOL CORP
1002	US5036235A	1991	XEROX CORP	320	US9692278B2	2017	PIERBURG GMBH & CO KG NEUSS
1000	US5075606A	1991	LIPMAN LEONARD H	307	US9627934B2	2017	JOHNSON ELECTRIC SA
1005	US5164622A	1992	APPLIED MOTION PROD	199	US10056808B2	2018	POZMANTIR MICHAEL | POZMANTIR SERGEY
1014	US5086245A	1992	SL MONTEVIDEO TECH	154	US9954417B2	2018	MILWAUKEE ELECTRIC TOOL CORP
952	US5355043A	1994	NIDEC CORP	224	US10286345B2	2019	CLARCOR INC
926	US5418416A	1995	PAPST MOTOREN GMBH & CO KG	225	US10323640B2	2019	CLARCOR INC
921	US5528096A	1996	SANKYO SEIKI MFG CO LTD	285	US10432079B2	2019	NY THOU M

812	US5844338A	1998	SIEMENS CANADA LTD	96	US10530220B2	2020	MILWAUKEE ELECTRIC TOOL CORP
883	US5838877A	1998	ITT AUTOMOTIVE ELECTRICAL SYST	195	USRE48231E1	2020	ZHONGSHAN BROAD OCEAN
888	US5710474A	1998	CLEVELAND MOTION CONTROLS	142	US11090453B2	2021	RESMED MOTOR TECH
809	US5903118A	1999	MAGNETIC MOTORS	9	US11837926B2	2023	BLACK & DECKER INC
847	US5861696A	1999	MAXTOR	15	US11786677B2	2023	RESMED MOTOR TECH
822	US5907205A	1999	HERMAN ROBERT WAYNE | ELLIOTT TIMOTHY JAMES	7	US11855521B2	2023	BLACK & DECKER INC

Table A.9: Patents on the main paths of the induction motor subdomain. Note: 12 HPPs out of 31 Nodes.

Node	Number	Year	Current assignee	Node	Number	Year	Current assignee
3	US4081726A	1978	LINEAR INT	112	US5952764A	1999	FANUC LTD
4	US4095149A	1978	BRUNSON GLEN & NEUROLOGICAL ASSOC TUCSON PENSION & PROFIT SHARING PLAN | WANLASS CRAVENS L	114	US6058596A	2000	GENERAL ELECTRIC CO
18	US4309635A	1982	HITACHI LTD	120	US6177750B1	2001	RELIANCE ELECTRIC TECH
28	US4409506A	1983	HITACHI LTD	142	US6822369B2	2004	PONG TA CHING
29	US4446416A	1984	WANLASS CRAVENS L | BRUNSON GLEN & NEUROLOGICAL ASSOC TUCSON PENSION & PROFIT SHARING PLAN	162	US7296409B2	2007	CUMMINS TURBO TECH
42	US4651040A	1987	ROBERT BOSCH GMBH	164	US7459815B2	2008	LG ELECTRONICS INC

45	US4777396A	1988	HITACHI LTD
47	US4808868A	1989	S P C HLDG COMPANY
64	US5029265A	1991	STAATS GUSTAV W
79	US5444319A	1995	FANUC LTD
75	US5378952A	1995	ERA ELEKTRONIK REGELAUTOMATIK
82	US5565752A	1996	WISCONSIN ALUMNI RES FOUND
91	US5734217A	1998	AURA SYST INC
99	US5797718A	1998	U S PHILIPS CORP
96	US5793145A	1998	FCA US
93	US5763975A	1998	U S PHILIPS CORP
192	US8492950B2	2013	GE GLOBAL SOURCING LLC
193	US8511367B2	2013	GM GLOBAL TECH OPERATIONS LLC
204	US8878412B2	2014	KS RESEARCH SA
200	US8740584B2	2014	MITSUBISHI ELECTRIC CORP
228	US9923439B2	2018	MOTOR GENERATOR TECH INC
227	US9923440B2	2018	MOTOR GENERATOR TECH INC
254	US10666113B2	2020	JOHNSON CONTROLS TYCO IP HLDG LLP
267	US10998802B2	2021	MOTOR GENERATOR TECH INC
285	US11757328B2	2023	JOHNSON CONTROLS TYCO IP HLDG LLP

Table A.10: Patents on the main paths of the permanent magnet motor subdomain. Note: 24 HPPs out of 34 Nodes.

Node	Number	Year	Current assignee
1529	US3968390A	1976	HITACHI LTD
1522	US4067101A	1978	SUWA SEIKOSHA CO LTD
1516	US4144469A	1979	HITACHI LTD
1514	US4139790A	1979	RELIANCE ELECTRIC CO
1501	US4358697A	1982	SIEMENS ALLIS
1506	US4403161A	1983	HITACHI LTD
1497	US4469970A	1984	GENERAL ELECTRIC CO
1252	US6008559A	1999	PANASONIC CORP
1245	US5962944A	1999	FUJITSU GENERAL LTD
1232	US6034459A	2000	HITACHI LTD
1226	US6218753B1	2001	PANASONIC CORP
1176	US6486581B2	2002	SANYO DENKI CO LTD
1167	US6794784B2	2004	KK TOSHIBA | TOSHIBA IND PROD MFG
1021	US7105971B2	2006	DENSO CORP

1487	US4433261A	1984	OKUMA TEKKOSHO	1074	US7233090B2	2007	ROBERT BOSCH GMBH
1450	US4742259A	1988	FRANKLIN ELECTRIC CO INC	985	US7425786B2	2008	HITACHI ASTEMO LTD
1454	US4845837A	1989	EMERSON ELECTRIC CO	940	US8106557B2	2012	MITSUBISHI ELECTRIC CORP
1424	US4922152A	1990	SIEMENS ENERGY & AUTOMATION INC	761	US9450472B2	2016	BLACK & DECKER INC
1406	US5097166A	1992	REULAND ELECTRIC	610	US9634531B2	2017	MITSUBISHI ELECTRIC CORP
1411	US5159220A	1992	GENERAL ELECTRIC CO	612	US10020699B2	2018	MITSUBISHI ELECTRIC CORP
1359	US5378953A	1995	FANUC LTD	526	US10116176B2	2018	MITSUBISHI ELECTRIC CORP
1342	US5510662A	1996	KK TOSHIBA	106	US11374473B2	2022	C & E FEIN GMBH & CO KG
1357	US5679995A	1997	SEIKO EPSON CORP	41	US11509193B2	2022	BLACK & DECKER INC
1281	US5886440A	1999	AISIN AW CO LTD	8	US11837926B2	2023	BLACK & DECKER INC

Table A.11: Patents on the main paths of the switch reluctance motor subdomain. Note: 13 HPPs out of 21 Nodes.

Node	Number	Year	Current assignee	Node	Number	Year	Current assignee
135	US4883999A	1989	PACIFIC SCI CO	72	US7420308B2	2008	VIRGINIA TECH INTPROP INC | REGAL BELOIT AMERICA
127	US4995159A	1991	PACIFIC SCI CO	60	US7781931B2	2010	DENSO CORP
125	US5111095A	1992	BALDOR ELECTRIC COMPANY	50	US8220575B2	2012	EVERETTE ENERGY
124	US5111096A	1992	EMERSON ELECTRIC CO	49	US8922153B2	2014	DENSO CORP
121	US5239217A	1993	EMERSON ELECTRIC CO	51	US8736136B2	2014	TOYOTA JIDOSHA KK
120	US5545938A	1996	BRITISH TECH GRP LTD	40	US10033233B2	2018	BOARD OF RGT THE UNIV OF TEXAS SYST

116	US5652493A	1997	BALDOR ELECTRIC COMPANY	33	US10348172B2	2019	BOOKS AUTOMATION US LLC
105	US5844343A	1998	EMERSON ELECTRIC CO	16	US10574116B2	2020	GM GLOBAL TECH OPERATIONS LLC
91	US5969454A	1999	PENGOV WAYNE	8	US10978980B2	2021	KARMA AUTOMOTIVE
89	US6028385A	2000	PENGOV WAYNE	7	US11444521B2	2022	BOOKS AUTOMATION US LLC
85	US6252325B1	2001	OKUMA CORP				

Table A.12: Patents on the main paths of the power electronics domain. Note: 9 HPPs out of 24 Nodes.

Node	Number	Year	Current assignee	Node	Number	Year	Current assignee
31	US5172784A	1992	VARELA JR ARTHUR A	235	US8336319B2	2012	TESLA INC
68	US5710699A	1998	GENERAL ELECTRIC CO	250	US8466652B2	2013	ARVINMERITOR TECH
88	US6163457A	2000	DAIMLERCHRYSLER RAIL SYST TECH	389	US9145065B2	2015	DR ING H C F PORSCHE AG
84	US6331365B1	2001	GENERAL ELECTRIC CO	246	US9290097B2	2016	GENERAL ELECTRIC CO
111	US6737822B2	2004	GENERAL ELECTRIC CO	448	US9527404B2	2016	ATIEVA USA INC
131	US6898072B2	2005	ROCKWELL AUTOMATION TECH	490	US9844995B2	2017	ATIEVA USA INC
139	US7081725B2	2006	VISTEON GLOBAL TECH INC	632	US10150383B2	2018	ATIEVA USA INC
142	US7049792B2	2006	GENERAL ELECTRIC CO	574	US10454290B2	2019	GENERAL ELECTRIC CO
123	US7032695B2	2006	ROCKWELL AUTOMATION TECH	620	US10220722B2	2019	FORD GLOBAL TECH LLC
124	US7177153B2	2007	ROCKWELL AUTOMATION TECH	635	US11167654B2	2021	GENERAL ELECTRIC CO

153	US7456602B2	2008	VITESCO TECH USA LLC | SIEMENS VDO ELECTRIC DRIVES | SIEMENS VDO AUTOMOTIVE CORP	872	US11230193B2	2022	FERRARI SPA
193	US7932633B2	2011	GENERAL ELECTRIC CO	988	US11571944B2	2023	FCA US

Table A.13: Patents on the main paths of the heat pump domain. Note: 19 HPPs out of 26 Nodes.

Node	Number	Year	Current assignee	Node	Number	Year	Current assignee
8	US4123916A	1978	FORD MOTOR CO	340	US8408012B2	2013	GENTHERM INC
23	US4384608A	1983	VISTEON GLOBAL TECH INC	369	US8851153B2	2014	HYUNDAI MOTOR CO LTD | KIA CORP | DOOWON CLIMATE CONTROL | HANON SYST
60	US4688394A	1987	TECH UN	418	US9561704B2	2017	DENSO CORP
79	US4991405A	1991	SANDEN CORP	447	US9650940B2	2017	DENSO CORP
97	US5388421A	1995	NISSAN MOTOR CO LTD	415	US10232702B2	2019	DENSO CORP
109	US5524446A	1996	HONDA MOTOR CO LTD	582	US10655504B2	2020	DENSO INTERNATIONAL AMERICA
115	US5598887A	1997	SANDEN CORP	683	US10814692B2	2020	HYUNDAI MOTOR CO LTD | KIA CORP
118	US5641016A	1997	DENSO CORP	560	US10940740B2	2021	DENSO CORP
160	US5899086A	1999	CALSONIC KANSEI CORP	743	US10914225B1	2021	HYUNDAI MOTOR CO LTD | KIA CORP
167	US6047770A	2000	DENSO CORP	744	US11028764B2	2021	HYUNDAI MOTOR CO LTD | KIA CORP
222	US6640889B1	2003	HANON SYST	736	US11318816B2	2022	HYUNDAI MOTOR CO LTD | KIA CORP

253	US6862892B1	2005	HANON SYST	791	US11479077B2	2022	HYUNDAI MOTOR CO LTD | KIA CORP
302	US8517087B2	2013	BERGSTROM INC	804	US11613164B2	2023	HYUNDAI MOTOR CO LTD | KIA CORP

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