sustainability

Article

Challenges for the Adoption of Electric Vehicles in Thailand: Potential Impacts, Barriers, and Public Policy Recommendations

Kantapich Preedakorn *, David Butler and Jörn Mehnen

Department of Design, Manufacturing and Engineering Management, Faculty of Engineering, University of Strathclyde, Glasgow G1 0LZ, UK
* Correspondence: kantapich.preedakorn@strath.ac.uk; Tel.: +66-025105244

Abstract: The impacts of electric vehicles (EVs) to the current transportation and logistics system are an emerging topic that has recently garnered public interest in many countries. Several developing countries that rely on the large amount of production in automobiles manufacturing are preparing to adopt national strategies to mitigate the negative impacts from the shift toward electric vehicles. In addition, the restructuring of the transportation system and traffic regulations to prepare for the integration of electric vehicles into the current transportation model is also an important concern for policy-makers. The study of potential impacts and barriers regarding the adoption of EVs would provide better insights that could aid the implementation of public policy. The topics that will be discussed here are both from technological standpoints such as differences in the general properties of EVs in comparison to internal combustion engine vehicles (ICEVs), and social and environmental standpoints which are predicted to be pivotal drivers for their adoption. These features are collectively analyzed to aid the relating implementation of industrial, transportation, and environmental public policies. Moreover, additional policy recommendations for the situation in Thailand are proposed based on this discussion. It is concluded that extensive public policy framework for the adoption of EVs and the development of EVs manufacturing industry is essential for developing countries with less technological readiness to effectively integrate this new type of vehicular technology into its industrial and transportation economy.

Keywords: electric vehicle; innovation cluster; technological disruption; complex system; automotive industry; public policy

check for updates

Citation: Preedakorn, K.; Butler, D.; Mehnen, J. Challenges for the Adoption of Electric Vehicles in Thailand: Potential Impacts, Barriers, and Public Policy Recommendations. *Sustainability* **2023**, *15*, 9470. https://doi.org/10.3390/su15129470

Academic Editors: Francisco Manzano Agugliaro and Esther Salmerón-Manzano

Received: 21 September 2022
Revised: 30 November 2022
Accepted: 2 December 2022
Published: 13 June 2023

1. Introduction

1.1. History and Future of Electric Vehicles

According to the general public at the present, the electric vehicle industry might be a novel technological development that will be highly impactful towards the future of ground transport [1]. However, the origin of electric vehicles actually dates back to the beginning of the automobiles [2]. Electric cars were introduced around the same period when internal combustion engine cars were introduced to the market [3]. Nonetheless, the development of EVs was discontinued after the breakthrough in manufacturing cost-reduction and quality control in the manufacturing of internal combustion engine vehicles (ICEVs), which resulted in an array of significantly cheaper and less defective ICEVs in comparison to EVs [4]. At the start of the new millennium, advancing technologies and the looming threat of global warming drove many car manufacturers to revive the research and development of electric vehicles. The main competitive disadvantage for electric vehicles is the low driving range per one cycle of a fully-charged battery, and the cost of materials for battery manufacturing [5]. This issue leads to insufficient demand for EVs, which prevents vehicle manufacturers from operating a financially feasible production cycle. Nevertheless, it is revealed that the nationwide adoption of clean energy vehicles such as battery-based EVs could be extremely beneficial to the countries that import large amounts of fossil fuel [6,7].

If the manufacturers could overcome the barriers of battery capacity and its manufacturing cost, the adoption of electric vehicles throughout the globe could rise significantly.

The lack of market demand was identified as one of the most prevalent obstacles for a wider adoption of electric vehicles [8]. There were many researchers that studied the utilization of public policy interventions to facilitate the market diffusion of electric vehicles. Among the earliest examples was the study regarding the role of zero emission vehicles (ZEV) mandate in California, USA. This study was conducted to design a predictive mathematical model to calculate the cost-benefit outcome of the transition from ICEVs to EVs from 2015 to 2050 [9]. This model was further used in a calculation of nationwide environmental and economical outcome for the whole country, both within the state of California, and the states in USA which adopted this mandate. The results showed that the adoption of electric vehicles would provide substantial benefits in terms of the reduction in greenhouse gas emissions, the reduction of petroleum usage, and the improvement of air quality [10]. Nevertheless, it is also asserted that constant government subsidies are mandatory for ZEV to progress. This imbursement would increase the initial cost for this public policy campaign and would likely incur net loss to the government. However, it is presented that the benefits would far exceed the overall cost and the break-even point will be prior to 2050, granted that the actual circumstance in the global economy would not notably differ from the assumptions within the model [11]. The projection from this model also showed that battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) will be less costly to be manufactured than their internal combustion engine vehicles (ICEVs) and hybrid electric vehicles (HEVs) counterparts after the year 2040 [10]. If this prediction is correct, then cost will be the main driving force for the significant growth of the electric vehicles market during the decade of 2030–2040.

According to the statistics in September 2022 from the Thailand Automotive Institute (TAI), there were an increase of 182%, 80%, and 384% for newly registered hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles, and battery electric vehicles (BEVs) compared to the same period in the previous year [12]. This indicated that there are more interested from the Thai population regarding electric vehicles, especially for battery electric vehicles. Additionally, this increment is sustained throughout the past 5 years, even though there was less increment in the year 2020 and 2021 due to the slowdown of domestic and global economy related to the COVID-19 pandemic. For charging stations, Thailand has a total of 944 locations throughout the country. More than half of these locations have been recently installed in the previous 3 years and the biggest owner is Energy Absolute Co. Ltd. (EA), which owns a total of 417 charging stations [13]. The increase in both electric vehicles and charging station was in accordance with national policy in Thailand, in which the government intensified the promotion for the usage of electric vehicles to the general population. This increment is expected to be steadily sustained during the next decade. However, there was still no fully integrated policy plan that connected all aspects of the EV industry to ensure that the implemented policy has been adopted effectively and acceptably with the domestic stakeholders and actors. This research is the first step to rectify this error by being the foundation towards the next step that the Thai government should take to shift the country's transportation system into a more environmentally friendly alternative.

1.2. Paper Structure

The purpose of this paper is to explore the industrial and related aspects of electric vehicles and apply them in the discussion regarding their potential impacts toward the industrial, economics, and environmental situation in Thailand. The barriers to the countrywide adoption of EVs from the viewpoints of multiple stakeholders in the Thai EV industry are investigated. Consequently, preventive measures in the form of policy recommendations are suggested to mitigate public resistance to the adoption of EVs which might manifest from these barriers. The results and discussion of this paper are separated into three main sections.

- Potential impacts of the electric vehicles in Thailand.

- Current barriers to the adoption of electric vehicles in Thailand.
- Policy recommendations for the Thai government.

The main contents in this research paper integrate the review of the literature surrounding the current situation of the electric vehicle industry on a global scale into the context of the Thai automotive industry. This context is very likely to also apply for other developing countries that benefit from a labor-intensive automotive manufacturing industry. This paper provides academic reflection in both the general situation regarding the impacts and barriers of EVs in a global scale and the specifics that are prevalent in Thailand. The first section reviews the impacts by focusing on the expected benefits that could be derived from the increased adoption of EVs and a potential paradigm shift that could occur along with this change. This includes the disruption of ICEVs manufacturing supply chain and the existing energy and transportation infrastructure. This issue is heavily related to the feasibility of the EVs manufacturing industry and the cultivation of the EVs market. The second section explores some of the most imperative barriers to the adoption of EVs, and the obstacles in the implementation of public policy to hasten the transition from ICEVs to EVs. These barriers are identified through the existing literature and information that was collected from policy and industry experts in Thailand. The last section is a brief proposal of policy recommendations for Thailand to address the issues that could originate from the barriers. In addition, the examples of pictorial framework to support policy implementation in each section are also presented with associated figures.

2. Research Methods

The data that are related to the 3 main topics that are discussed in this paper were gathered from several stakeholders in the Thai EV industry. The interviewees included bus manufacturers, government agencies, research groups who would have research applications for the e-bus industry, potential e-bus purchasers, and users. There were 12 participants in total and the interviews were all conducted within the year 2020. The main objective of this data collection was to collect relevant information to prepare and formulate a convincing policy plan that would be impactful towards the development of the electric vehicles industry in Thailand. Ultimately, this policy plan should be able to accelerate the adoption of electric vehicles in the Thailand transportation system. The most recent information regarding the development in the electric vehicle industry in Thailand were gathered via several semi-structure interviews. The sample group of these interviews included five major types of stakeholders: policy-makers, researchers, manufacturers, operators, and users. The interview questions were specifically designed for each group of stakeholders according to the expected contribution that each group could provide. This included their opinions on the potential of electric vehicles in the Thai transportation system in both the current situation and the future. For example, an interview with an academic researcher was primarily focused on the development of relating technologies to EVs rather than market condition of the EV industry. All individual interviews were recorded by a voice recording device. These recordings were transcribed into text format in the English language during the process of data analysis.

In addition to the insights that were recorded in this paper, the formulation of a public policy framework for an EV industry cluster in Thailand was also concurrently developed as a thesis to submit for a doctoral degree at the University of Strathclyde. Since the data were collected from multiple groups of people with varying degrees of knowledge regarding electric vehicles, the process of data analysis was considerably challenging. To alleviate this issue, the questions in these interviews were maintained to be relatively similar across each group, with the focus toward the gathering of sufficient information in five aspects of the electric vehicle industry in Thailand: the actors within the system, the current progress of the industry, the feedback and sensitivity toward the industry, the strategy utilized by stakeholders, and the metrics to measure stakeholder's performance. This boundary was designed to facilitate the transition of the analyzed data into the inputs for the formulation of a policy framework. Most of the results and discussion section of this paper are the conceptualization of the themes which were extracted from the data by the process of thematic analysis.

Thematic analysis is often used to identify recurring topics, themes, and concepts inside a set of texts from the transcription of an interview or other text-based qualitative data (Guest, 2012). The full transcriptions of the interviews were written in text format during the first step of data analysis. This process also included the translation from Thai to English. All of them were combined into a single coding sheet which summarized similar questions and answers together. Then, all responses were collectively analyzed and categorized into multiple grouping of major themes which are shared by these responses. This process was repeated multiple times to appropriately conceptualize the interview responses into multiple perspectives. Finally, these themes were recorded and marked according to the frequency that they appeared across multiple interviews. This process would present each theme in order of their perceived importance among interviewees and will be vital to the identification of gaps in the electric vehicle industry in Thailand.

3. Potential Impacts of Electric Vehicles

3.1. Environmental Impacts

The perception of the general public towards global warming and the deterioration of the world environment is increasingly dramatic [14]. The adoption of EVs is one of the most popularized forthcoming solutions to reduce vehicle emissions pollution in many developed and developing countries [15]. Electricity is considered a cleaner energy source for vehicles in comparison to petroleum-based energy because of the higher energy efficiency of an electrical engine when compared to an internal combustion engine. Additionally, these environmental benefits would be amplified if the country utilized relatively cleaner energy sources in the generation of electricity. This will be the case for Thailand since its current domestic electricity generation is typically achieved through the use of natural gas (70%) [16].

Approximately 50–60% of air pollution in Thailand originates from vehicle emissions [17]. The focal point of the incremental pollution problem in Thailand is located around the vicinity of urban areas such as Bangkok, Chiang Mai, and Nakhon Ratchasima. The major cause of the problem is the overutilization of diesel engine vehicles in commercial logistics, especially the vehicles that are below certified emission standards [18]. In Bangkok, the emission from diesel buses and trucks contributes the largest proportion of road-based pollution throughout the country [19]. This leads to a multitude of air pollution problems, including an excessive amount of photochemical smog, carbon dioxide, and fine particulate matter ($PM_{2.5}$), all of which are hazardous to physical health. The seriousness of this hazard is amplified by the fact that all the problematic areas are highly populated. Since a large proportion of public transport buses in Bangkok are regulated by the government, the change towards electric buses in public transportation could be considered as the most reasonable solution for the vehicular pollution problem in Bangkok. The initiation of an electric vehicle ecosystem could also lead to the implementation of a vehicle's recycling and disposal industry, which would be able to further mitigate environmental issues that could stem from poor waste management in the automotive industry [20].

Outside city areas, Thailand also faces additional air pollution from the burning of agricultural crops and forest fires which contributes 35% towards the total air pollution in Thailand [17]. However, this problem is difficult to control due to the wider area of impact and the randomness of occurrences. This phenomenon is most likely to happen due to the exposure of strong sunlight coupled with an extremely dry climate [21]. In addition, some crop residues are intentionally burned despite the prohibitive regulations from the government. This is due to the practice being perceived by farmers as a cheap and effective method to quickly clear harvested fields, with additional combative features against pestilence and weeds [22]. In contrast to urban areas, the adoption of electric vehicles would provide less relative environmental benefits to the rural parts of the country and would be more difficult to effectively implement due to the technical limitations of EVs.

3.2. Energy Consumption

The adoption of EVs is predicted to prominently reduce the amount of gasoline consumption at a national level [23]. This reduction would be especially beneficial to the country that incurs a large amount of trade deficits in crude oil imports. Currently, Thailand has consistently imported crude oil worth over 17 billion USD in every calendar year, with the exception of 2020, throughout the last decade [24]. The reduction of fuel consumption in the transportation and logistical sector should be favorable to the state of the national economy. In addition, the wide adoption of EVs could also enhance usage efficiency of the generated electrical energy. This could be accomplished by the implementation of an energy management system utilizing vehicles to grid technology (V2G) with EVs as an additional energy storage option [25]. The successful implementation of this technology could reduce electricity generation cost, since less optimization would be required for the current national production of electricity [26]. However, this benefit is highly dependent on different charging scenarios. The set-up of proper energy policy and plan is required to control the possible uncertainties that could negatively affect the projected reserved power due to the increase in demand during a certain time [27]. Nevertheless, the incremental adoption of EVs is continuing to be an aspiring energy-based target for the Thai government.

3.3. Disruption to the Existing Automotive Supply Chain

There are ongoing debates in the discipline of technology and innovation studies regarding which emerging technology should be considered as "disruptive" [28]. Electric vehicles are also one of the technologies that could be classified into this conundrum. It is asserted that the existing definition of "disruptive innovation" was not sufficient to identify a disruption among emerging technologies. The term is normally used to classify the technology in hindsight, which means that the impacts of the technology in question have already been assessed in actual industrial environments before the classification [29]. This limitation causes the notion of "disruptive innovation" to bear less weight in the considerations of several parties, who could potentially inspire changes within the industry [30]. The use of three criteria to identify disruptive technology were proposed by Hardman, Steinberger-Wilckens, and van Der Horst [31]. First, this technology needs to disrupt the current market leaders, as it is being heavily invested by new entrants. Second, this technology needs to disrupt end users, by changing how the product is used. Third, this technology needs to disrupt the current infrastructure, which was built to support previous technology. By following these criteria, the adoption of EVs in Thailand could be classified as technological disruption because the last two criteria are met. This circumstance will be discussed in this and the next section (Sections 3.3 and 3.4).

The automotive industry constitutes a large portion of the Thai economy. There are currently 19 assembly plants and 2200 OEMs factories in Thailand. They contributed to 850,000 employees, with the annual value of all manufactured vehicles totaling 61.856 billion USD [17]. The global trends and progression of electric vehicles threatens the future stability of Thailand's automotive industry because of the lack of domestic research and development in electric vehicles. Additionally, the current infrastructure in the Thai automotive industry was almost completely engineered for the research and manufacturing of ICEVs. If ICEVs are superseded by EVs as a globally preferred medium in road-based transportation, the Thai automotive industry would be forced to deal with this paradigm shift in the industry. In preparation for this event, there was a recent surge in the number of public policy plans entailing transitional strategies, which were aimed toward stakeholders within the existing supply chain of the Thai automotive industry [32].

In addition to the change in supply chain infrastructure, the Thai economy might also suffer from the loss in automotive exports from the potential reduction in global demand for ICEVs [33]. If the domestic research and manufacturing sectors for automobiles could not embed itself into the global supply chain of electric vehicles industry soon, Thailand could be forced to make a choice between importing electric vehicles from overseas and continuing to use ICE vehicles in its transportation system. The first choice would lead to a potentially large international trade deficit for the country. In contrast, the second choice is also risky, considering that the current Thai automotive supply chain is strongly dependent on the foreign multinational corporations (MNCs) [34]. If these corporations discontinue their support for ICEVs or relocate their production base to other countries, a large amount of job losses in the industry would be incurred. Therefore, the redevelopment of the domestic supply chain and market towards both pure and hybrid EVs is regarded as the ideal course of action [35].

3.4. Vehicle's Usage Pattern

Electric vehicles have several differences from ICEVs which might reinforce users to respectively adjust their driving behavior. Most formats of EVs usually have two common disadvantages in comparison to ICEVs, both of which are related to the lagging of technical performance in energy storage systems. These disadvantages are the cruising range of vehicles and the time that is required for the charging process [36]. Driving patterns are expected to change considerably due to a shorter cruising range of EVs because of 'range anxiety'. People are expected to drive their vehicles more conservatively in order to conserve the remaining energy [37]. Furthermore, EVs would have more idle time due to a significantly slower charging speed compared to the speed of the refueling process in ICEVs [38]. Range anxiety and slower charging time might result in an aversion towards wasting vehicle's energy [39]. Additionally, electric vehicles would also have different lifespans from ICEVs and require different processes in repairing and maintenance. The current performance of electric vehicle's battery and fast charging stations is not likely to match the quicker refuel process of the ICEVs in the near future [40]. These circumstances will likely change the general usage patterns of the consumers. In summary, electric vehicles would be impactful toward user's behavior on how they use their automobiles and could be considered as disruptive technology by a criterion that was outlined in the last section.

The provision of charging infrastructure is another important issue that is closely related to the vehicle usage patterns of EVs. For exclusive urban transportation, the concern regarding the availability of charging stations would be less prominent because of the short travel distance. In Norway, the collected data showed that most users prefer charging their cars at home during the night [41]. Nevertheless, the installation of charging stations would be necessary towards the growth of EV adoption. This is most likely to be the case for the early stages of EV market development in any country. It is asserted that a charging station business should be stimulated, otherwise the EV market would be limited only in smaller areas [42]. For Thailand, governmental support might be required for the expansion of charging infrastructure. Additionally, the provision of home-charging equipment should also be especially focused on the quality assurance in safety features and charging efficiency [43]. The amount and spread of fast-charging stations and slow-charging solutions are expected to be highly impactful towards the usage patterns of EVs because they are directly related to the confidence among many potential users.

3.5. Personal Value for Vehicle's Owners

The preference toward electric vehicles among potential users often coincides with the perception of economic savings that can be derived from the reduction in fuel costs. It was found that potential buyers of EVs would include approximately 5 years of fuel-saving into their purchasing decision and are willing to pay a premium price for EV based on this assessment. In addition, they also prioritize good driving range and charging time characteristics of EV over pollution reduction and vehicles performance [44]. Price acceptability was also found to be in the highest echelon of importance in the recent study in several big cities of China, which is presumed to be the current biggest EV market in the world [45]. Government subsidies and the progression rate of energy storage technologies are identified as the most important factors that could lead to the reduction in the cost of EV mass production [46]. The reduction of EV pricing to an acceptable level is expected to promote market diffusion from early adopters towards a larger portion of customers.

The importance of EV pricing led to several academic studies that were made to assess the potential growth of EV market by associating user's acceptance with the econometrics of EVs for personal use. Many of these studies utilized mathematical methods to formulate the total cost of ownership (TCO) of an EV in order to gain extra insight on the feasibility of the EV market [47]. It is asserted that the model should be responsive to the shifting technological variables or policy instruments that are used by the government. Multiple variable regression models are often applied because economists could easily include additional units into a model [48]. The current global trends of public policies relating to the reduction of EV pricing are mostly limited to fiscal policies. This includes the provision of tax credits to EV buyers, or the distribution of subsidies to EV manufacturers [49]. It is stated that these fiscal policies are not yet fully effective in terms of boosting sales and the adoption rate of EVs [50]. Aside from the topic of EV pricing, there are other esoteric economic factors to be considered. For example, the model to calculate total cost of ownership of an EV could also include the cost of charging services. The complexity of TCO models are expected to be significantly higher because the pricing structure of charging stations would be strongly influenced by the complications in energy-mixed and capacity management of energy infrastructure [51].

3.6. Extension to CASE Technologies

The recent trends of the global automotive industry development recognize the importance of a group of complementary technologies that are interconnected with the development of electric vehicles. This group of technologies are often called by their acronym "CASE" or "ACES", which include connected vehicles (C), autonomous vehicles (A), and shared vehicles (S), in addition to electric vehicles (E). These interdependent technological features are predicted to be the cornerstone of the automobile manufacturing industry in the future, despite having separate courses of development in the past [52]. Each technology could provide a different type of facilitation to the current transportation system. Thus, it is expected that they would all contribute towards the manufacturing of a new generation of vehicles.

Electric vehicle technology is often seen as an enabling platform that would facilitate the integration of other branches of CASE technologies, because the redesign of vehicle's electrical systems are required in most applications [53]. There are many formats of EVs, but battery electric vehicles (BEVs) have recently gained a lot of momentum in the market. This is due to the steady progress of battery technology, with advances in both production cost reduction and performance improvement. Several technology experts predict that BEV's performance could catch up with ICE vehicles within a decade [54], which might negatively affect the ICEV market in the future.

Autonomous vehicles are a broad category of technology that covers a wide range of driving autonomy. While this technology usually refers to the ability of a vehicle to operate properly without human inputs, there are many different degrees of vehicular autonomy. This spectrum starts from simple automation that already exists in some of the current generations of vehicles such as the driving assist system, to the more advanced automation such as full autopilot of vehicles. Autonomous technologies will provide substantial benefits to traffic safety and general mobility of the transportation system [55].

Connected vehicles usually refers to the connectivity of vehicles and their driving system to the external environment such as the traffic control system and energy grid. These connections can be seen as a portion from the encompassing topic regarding the internet of things (IOT), which have the capability to enhance the amount of information that can be transferred from the intra-vehicle network to the inter-vehicle network, with greater transmitting speed [56]. This feature would provide substantial benefits to traffic and vehicle regulation and might partially mitigate congestion problems in a certain area.

Lastly, sharing vehicles is the ideological movement that is embedded inside societal and technological development to improve transportation efficiency by the reduction of wasteful traveling activities [57]. In fact, vehicle sharing is not a new topic. Humans utilized this concept for a very long time in the various forms of public transportation such as trains, planes, or buses. However, the potential to maximize transportation efficiency is higher than before because of the potential implementation of CASE technologies. As a result, a shared vehicle model will provide substantial benefits toward land usage and public mobility.

3.7. Traffic Congestion and Road Safety

Traffic congestion can cause a certain level of economic loss to a country due to unnecessary energy expenses and the reduction of national productivity from the increment of idle time in the traffic. From the data that were recorded in 2017, it was estimated that traffic congestion in Bangkok incurred a total of 500 million USD opportunity losses for Thailand [58]. The introduction of vehicles with CASE technologies could be an opportunity for the government to adopt several public policies that aim to limit the number of ICEVs on the road. Additionally, the connection of new generation vehicles to traffic infrastructure could also vastly improve the utilization rate of public transport and traffic management. It can be concluded that the effective implementation of transport policies would be highly impactful towards the mitigation of traffic congestion issues [59]. The technological improvement of EVs might not have a strong direct impact on traffic congestion and road safety, but EVs themselves would be an important modular platform for the development of other CASE technologies.

The adoption of autonomous vehicles and connected vehicles might lead to smoother traffic flow and the improvement of traffic monitoring systems, respectively. Driving distance between each vehicles could be reduced significantly in higher levels of autonomous driving [60]. This includes shorter headways between vehicles at traffic signals, which would result in the improvement of intersection efficiency, especially in crowded city areas [61]. As a result, less traffic congestion is expected from this upgrade of road space utilization. In some cases, additional lanes on the freeway could be newly assigned because of extra road space. Gap reduction and constant travel velocity of the traffic might yield a more reliable travel time for commuters, which could bolster national productivity in the long run.

There are potential benefits for the reduction of road accidents, both in terms of politics and economics. Thailand has been ranked consistently high in road fatality rates. Statistically, there are 44 deaths from traffic accidents in every 100,000 people who live in Thailand [62]. In 2018, approximately 20,000 people were killed by traffic accidents. A significantly higher number of crashes that resulted in severe injury were also recorded [63]. The annual economic loss is estimated at around 3.56 million USD per year [64], which is significantly higher than the loss from countrywide traffic congestion problems. The challenge for autonomous vehicles is to design a system that can perform accurately in imminent crash situations. Nonetheless, it is predicted that the future progression of technology would eventually overcome many of the current obstacles that prevent the autonomous systems from properly functioning in complex environments [65].

4. Current Barriers to the Adoption of Electric Vehicles

4.1. Vehicle's Price and Investment Decision of Stakeholders

Since the price barrier for electric vehicles is still too high for many potential buyers, the competitiveness of EVs as a product when compared to ICEVs should be properly addressed by policy-makers prior to the revelation of an EVs adoption program. Singapore is an ideal setting for the full adoption of EVs in the country because of its status as a small and well-organized city state [66]. A variation of a TCO model was used to assess pricing competitiveness of EVs in Singapore. It was asserted that the current speed of transition toward EVs is not fast enough for the government to observe clear economic and environmental impacts [67]. Hence, public policy focus should be shifted from EV's demonstration to proper adoption in actual transportation systems. Singapore normally inflates the cost of private cars for citizens, in order to limit the amount of vehicles and mitigate traffic congestion [68]. This could be an opportunity for the government to exclusively exempt additional charges for EVs. This fiscal policy is quick to implement, but the effects will be apparent to the consumers. Therefore, this regulation could potentially generate a sizable impact toward the growth of the EV market.

In Thailand, the largest obstacle for Thai manufacturers is the lack of economies of scale in the domestic market, which prevents competitive pricing of EVs. Domestic demand for EVs were reportedly not big enough for several automotive enterprises to maintain their profitability due to high fixed costs in the installation of EV's production line [35]. This weakness would result in less competitive pricing of EVs until an ample export market is established. Therefore, manufacturers would require a stronger value proposition or marketing scheme to sell their product despite the price disadvantage to ICEVs. Nevertheless, the price of vehicles is the main driver for purchasing decisions in both public and private uses from the customer's perspective [69]. For transportation services such as public buses, it is asserted that the acquisition of electric buses have to be in concert with the turnover of old buses [70]. This circumstance is essential to maintain economic efficiency in the operation. Unfortunately, the current offerings of electric vehicles is often seen as an infeasible alternative for several bus operators in Thailand [71]. It is expected that the alteration of pricing structure for public bus services would be difficult since it is a fundamental means of public transportation in Bangkok.

4.2. Technical Specification of EVs

As mentioned in the previous section, the driving range of EVs is often regarded as the most impactful technical disadvantage in comparison to ICEVs [72]. Specialized technological expertise is required for the manufacturing of EVs with an acceptable level of technical performance. In the case of battery electric vehicles (BEVs), many of the incumbent original equipment manufacturers (OEMs) are still aiming to produce parts for BEVs. However, the components of powertrains and energy storage systems in BEVs require novel approaches in the manufacturing process, which are normally possessed by a different set of suppliers [73]. This disruption would create another challenging prospect in the management of the automotive supply chain and might be harmful to several stakeholders.

In general, there are two types of BEVs that are being manufactured if they are categorized by technology specifications. The first type is mass market EVs that are produced with a purpose to minimize the offering price so that they could be competitive in the current market of automobiles. In this category of BEVs, several areas of technical performance including driving range are relatively inferior to their ICEVs counterparts because of the limitation in research and manufacturing costs [74]. Mass market BEVs were struggling in terms of sales despite being heavily promoted by government subsidies. It was deduced that mass market BEVs do not sufficiently provide additional value to potential purchasers. Additionally, they also often command a higher price than conventional vehicles in the market [31].

The second type of BEVs are generally manufactured to serve a niche market which constitutes of early technology adopters. The initial stage of Tesla is the most prominent example of a manufacturer in this category. Their initial design of BEVs dismissed cost reduction in favor of high-end features, such as integrative digitalization of driving systems, improved car performance, comparable range to ICEVs, and a high quality chassis [75]. This marketing strategy allowed them to earn a remarkable sum of funding which could be reinvested into other market segments, including a more affordable BEV market which has future potential to improve its driving range based on the advancement of energy storage technologies. Nevertheless, the introduction of BEVs to mass market is still predicted to be difficult due to the technological lock-in of petroleum vehicles, and the issues of awareness and public perception [76].

4.3. Confidence in New Technology

Technological lock-in of ICEVs that affect transportation infrastructure contribute to the high levels of barriers to entry for EVs. This issue could be broken down into three sub-topics; economies of scale of the incumbent, learning difficulties, and network effects [31]. Conversely, these factors are currently offset by several developments within the automotive industry, including public policy supports to promote the proliferation of EVs, the likelihood of technological breakthrough in battery manufacturing, the shift in public preference toward electric vehicles, and strong support of the scientific community [77]. Naturally, the readiness of infrastructure is the main barrier for the growth of electric vehicles. A pre-developmental phase of setting up charging infrastructure would be required in order to increase the market penetration for EVs in rural areas and inspire confidence to users. However, this could also prove to be a risky endeavor since the technological development is still ongoing. There is no guarantee which technology would be the next major driving force for the automotive industry, especially when a large amount of research on alternative energy sources for land transport have been conducted [78–80].

It was asserted that the lack of awareness and confidence among end users negatively affects the demand for EVs [81]. Governments should make sure that there is public awareness of the intention to promote the EV usage in the wider scale before making decisions to enforce them in the transportation system. In addition, there should be more communication channels between stakeholders and policy-makers to facilitate information sharing. The information that is being exchanged should focus on the feedback of stakeholders towards EVs that is related public policies that are adopted by the government. Positive feedback could lead to the strengthening of confidence among stakeholders in the supply chain [82]. It was found that the majority of stakeholders in Thailand, ranging from OEMs to system integrators have similar doubts on the profitability of the business model that would be driven purely by EVs [83]. The fact that EV technology is still in its initial stages in Thailand further dampens the confidence among Thai stakeholders. Better communication regarding policy implementation could be able to counter this issue. Policy-makers should clearly explain that the supply chain is highly likely to be disrupted by the upcoming surge in the EV industry, to make all stakeholders aware of their individual risk.

4.4. Technological Capabilities in EV Research and Manufacturing

Technological capabilities are one of the largest hurdles for the progression of the electric vehicle industry in Thailand. Thailand still lacks sufficient technological specialization that could make them competitive in the global supply chain. They are currently unable to independently develop high performance batteries and electrical motors without the support from foreign companies [84]. Even in the case of ICEVs, the current level of capabilities among domestic original equipment manufacturers (OEMs) are not sufficient for them to break away from controlling multinational corporations (MNCs) [85]. The lack of skilled labor and trustworthy technological alliances in the global supply chain of EVs also prevents Thai companies from attaining higher levels of technological expertise. These issues could be traced back to the fact that several OEMs and domestic assemblers refuse to make a large amount of investment in the research and development for EV technologies [70].

The reason behind low research and development expenditure of developing countries is mostly due to the fact that there will be no guarantee for a good return on investment [86]. Product innovation in several developing countries is driven by the entrepreneurship of small and medium size business enterprises (SMEs). However, because of their limited financial resources and output capacity, the investment in research and development would be low in priority compared to the investment in other aspects that would give them more immediate and substantial results [87]. It was concluded that smaller firms would struggle in an attempt to acquire new technologies because of the rapid technological transition [88]. Despite the apparent shortcomings in economic value of research and development expenditure, many companies in developing economies are forced to comply. Without new products and services that would be created by these investments, it is difficult for any enterprise to maintain its business in an evolving economy such as the EV industry.

In terms of human resources, Thailand is faced with the problem of skilled labor shortages. Without effective knowledge transfer mechanisms or proper training methods, personnel with a deeper understanding in EV technologies would be too scarce for a gradual development of the EV industry [89]. Lower premium wages for technological experts also encourage them to relocate to foreign countries. Another gap in the topic of human resources that should be emphasized is the disparity in the level of expertise among the cluster of stakeholders within the supply chain. The current formation of electric vehicle clusters does not employ representatives from different sectors who are able to communicate with the same level of understanding in the topic of EVs [70]. This feature would be essential for effective communication between stakeholders with different backgrounds and business focuses.

4.5. Unclear Direction of Public Policy

Many actors in the Thai automotive industry agreed that the hesitation of stakeholders to invest in EVs is due to the lack of clear strategic direction from the government [90]. It was implied that this strategic direction does not just refer to the formulation of national strategy, but also the practical implementation of policy initiatives [70]. Activity-based objectives for each sector, which should be derived from industrial gaps, are not yet established. The examples of these objectives could be in the form of a technology localization plan to support EV manufacturers, or local content policy to establish a domestic market for EV's components. The comprehensive solution that could be made is the formation of an exclusive industry or innovation clusters for the development of the EV industry in Thailand.

The industry cluster for EV research and manufacturing in Thailand is anticipated to be a 'complex system' [91], which involves a diverse range of interactions between a large set of relating actors. The constant evolution and change of internal environment are common circumstances within this type of system [92]. These changes would not only affect a single specific element of the system but are likely to cause side effects to different parts within the system. Predetermined targets for each sector should be assigned before the formulation of public policies, to reduce the disorder that could negatively impact the effectiveness of policy implementation. There are three critical topics that are identified for the formulation and development of an industry cluster in Thailand [93]. This consists of the specification of organizational roles and boundaries within the cluster, the specification of intermediate gate-keeping organization, and the specification of financing policies and incentives.

The most urgent issue regarding financing policies is that the national budget was not currently utilized in meaningful activities for the adoption of EVs. It is commented that a large portion of financial resources were invested in several policy initiatives that could not produce substantial results for the EV industry [89]. Furthermore, there is still no credit policy for EV manufacturers, which discourages intensive investment in this technology. The dissemination of national strategies and public policies to stakeholders were often inaccurate due to the aggregation of information that include all sub-segments of the EV industry [70]. Information that was not methodically segregated often led to the misunderstanding of stakeholders regarding EV-related public policies. As a result, the translation from national-level public policy to organizational-level execution was difficult to implement.

5. Policy Recommendations

5.1. Creation and Management of Innovation Clusters

An innovation cluster is often defined as a virtual agglomeration among firms, in contrast to a geographical agglomeration in the classic definition of an industry cluster [94]. However, some practical examples of innovation clusters also rely on the notion of physical proximity. The example of this incorporation is the concept of the science park, which promotes the linkage and interaction between research institutions and the industry sector [95]. It is asserted that innovation clusters are more focused on technological knowledge and innovation, and are more likely to fully utilize the strengths and capabilities of the country or a specific region than industry clusters [96]. The transformation from industry clusters to innovation clusters requires a paradigm shift from efficiency-based productivity to research-based innovation. It is asserted that the creation of innovation clusters is accelerated by the high concentration of industry-academia cooperation and frequent knowledge sharing between parties [97].

It was emphasized that innovation clusters could occur naturally or be induced by public policy intervention [98]. There are naturally formed clusters which resulted from perpetual exposure to market mechanisms, for example Silicon Valley in the US. In contrast, there are artificially formed clusters, in which their formation is designated by central or local governing institutions. Several innovation clusters were created to emulate the success of naturally formed clusters. The example of these clusters was the Zhongguancun technology district in Beijing [99]. In fact, most of innovation clusters that have been recently established are induced by national development policy [100]. Innovation clusters are usually created to be the catalyst for innovative processes. They integrate both bottom-up and top-down interactions in one synergistic system [101]. There was a general consensus that new innovation is more likely to emerge when each actor within the system can freely interact [102]. This configuration is believed to be the ideal structure for the fostering of the innovation ecosystem [103]. It is reported that some innovation clusters have better technological performance in the absence of constraints from governing institutions [104]. However, it is not possible to quickly stimulate the EV industry without any form of policy intervention because of the existence of several barriers and limitations that were explained in the previous section of this paper. Thailand is also faced with its own set of gaps, which consist of both general limitations of the EV industry and specific limitations to its industrial environment (Table 1). The success factors in the development of an innovation cluster for the EV industry in Thailand would depend on several conditions and externalities that should be closely analyzed by the government. Nevertheless, the formation of an EV innovation cluster should be able to initiate necessary momentum for technological development, which would be the cornerstone for the growth of the EV industry.

Table 1. The current gaps of the Thai electric vehicle research and manufacturing industry (2021).

Capability Gap	• Few testing facilities for electric vehicles • Low research and development expenditure in the industry • The lack of skilled laborers with deep knowledge in electric vehicles • Low technological learning capacity • Poor labor market efficiency with high proportion of immigrant workforce
Policy Gap	• Require large amount of investment to transform the supply chain • No clear strategic direction on national scale • The lack of support for technology localization to manufacturers • Miscommunication between policy-makers and stakeholders • No evaluation scheme for the implementation of public policy

Table 1. *Cont.*

Market Gap	• The lack of public interest and actual demand for electric vehicles • Highly competitive overseas competitors • Low business incentives for new investors and ventures • The disruption of electric vehicles to other businesses • No integrative business model for the whole industry
Operational Gap	• Political issues with ICEVs-based organizations • The lack of research focus and prioritization of technological development • Low amount of charging infrastructure • Inertia of the large scale ICEVs-based supply chain • Require better integration of research and industry collaborative efforts

(Source: Consolidated by author).

5.2. Cost-Effective Solution to Obtain Technological Capabilities

There are several methods to absorb technological expertise from other entities. These methods should be analyzed not only for the difference in their financial cost, but also the expected results that could be distorted by technological complexity [105]. The most cost-effective solution is most likely the development of knowledge transfer mechanisms that are primarily based on domestic enterprises. It is asserted that the extensive information sharing network between researchers would be the most essential element for the system to attain sustainable innovation [106]. It is expected that this mechanism would greatly support the industrial development of the Thai automotive industry and facilitate the retention of its global competitiveness. However, the current lack of strength and longevity of stakeholder's collaboration is still an important topic that should be addressed [70]. Weak collaboration might originate from the fear of losing important information to the competitors. The most common presumption is that this circumstance would make the company lose competitive advantages [107]. Hence, it would be ideal for the government to regulate an optimal level of interaction within the cluster, to ascertain that important actors within the EV industry are willing to participate in this policy initiative. Since the Thai automotive industry does not have an abundance of experience in EV technology, case studies could be a valuable tool for the understanding of knowledge transfer mechanisms that are currently utilized by more developed contemporaries.

Tesla Motors could be a suitable example of a case study for Thai automobile manufacturers, since many of their manufacturing capabilities came from the acquisition of technological knowledge from other enterprises [108]. They proactively developed technology roadmaps to provide concise guidelines for technological development in the manufacturing process of EVs. The goal of this roadmap is to support the vision for Tesla to become the global market leader in the EV industry [4]. The study of their framework might reveal the information regarding the methods they utilized to obtain different branches of technology. There were four key elements to identify in this permutation of technology roadmap; market drivers, corresponding products, technologies that are required to develop the product, and technological gaps between existing capabilities and the minimum requirement in the manufacturing process. It could be summarized that battery capacity and charging rate are directly linked to the greatest number of market drivers. This implied that battery-related technologies should be prioritized in the acquisition if there are any internal gaps in terms of manufacturing capabilities. This roadmap could be modified by the inclusion of monetary value to market drivers and technological gaps. Therefore, it could enable many hesitant corporations to make appropriate investment decisions and thus accelerate the adoption of EVs. The method to formulate this technology roadmap is presented in Figure 1.

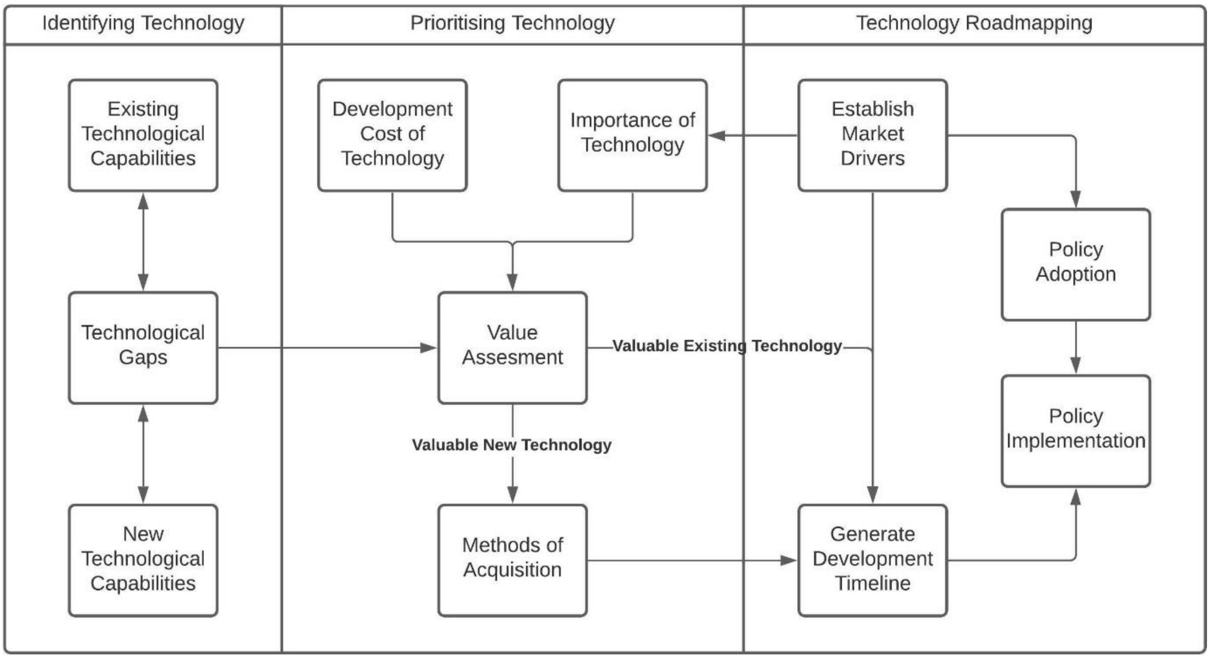

Figure 1. The formulation of a technology roadmap for policy implementation in the electric vehicle industry. (Modified from Technology Roadmap: A Roadmap for Tesla [4]).

5.3. Cultivation of Public Awareness and Market Demand for EVs

From the previous section, it has been established that privately-owned EVs are still not competitive enough to compete with ICEVs. However, the application of EVs in shared fleets might be a cost-effective alternative for potential buyers [109]. This application might still not be viable for large vehicles in Thailand since most of them use diesel engines which has a significantly cheaper fuel price than other alternatives. In Singapore, it was suggested that small fleet EVs would be highly competitive to ICEVs within 5 years, and the main competitor for EVs would be compressed natural gas vehicles (CNGVs) because of the relatively low projected energy cost [67]. However, this estimation did not include the possible inclusion of policy instruments that could be used to further reduce the cost of ownership for an EV fleet. Thus, it can be concluded that an EV fleet would likely become economically viable for users within the foreseeable future, but not without financial support from the government [110]. For example, the exemption of EV's registration fees might assist the EV industry to survive a highly competitive automobile market in Thailand. Nevertheless, additional non-fiscal policies should also be simultaneously implemented to accelerate the adoption of EVs, especially the campaign aimed to increase the amount of charging stations throughout the country.

Several European countries have recently adopted various public policies to promote the adoption of EVs. However, the growth of EV sales and the rate of market diffusion were still relatively slow [111]. In one study, several aspects of these policies were explored through the lens of uncertainty analysis to formulate a framework that could help policy-makers to pinpoint the pitfall of past attempts in policy implementation. The main concept of this study was to centralize the issue of market demand for EVs as the main driver for policy formulation, and make an assessment on how external uncertainties could generate adverse effects to the public demand for EVs, which render the implementation of policy ineffectual [112]. These market uncertainties for the Thai EV industry are compiled in Table 2. However, policy-makers should also be aware of the limitations of this framework. It is asserted that simplified models based on static parameters of uncertainties might not be able to fully capture the intricacies of a more complex system such as the automotive industry [113], especially when the current EV technology is constantly exposed to significant evolution during the past decade. Therefore, the application of this idea should also make a reservation for impending uncertainties that might strongly affect the growth of the EV market in Thailand.

Table 2. The current market uncertainties for the electric vehicle industry in Thailand (2021).

Consumer	• Preferences between ICE and EV based on demographics • Difference in prices, cost of ownership • Vehicles performance (mainly range and charging time)
Policy	• Choices of technologies (e.g., battery EV, hydrogen fuel cell EV, etc.) • Government stance on environmental issues • Financial condition of the government
Infrastructure	• Energy pricing (oil and electricity) • Investment on charging station and electricity infrastructure
Technical	• Unequal growth in the development between vehicle alternatives • Technology transfer and spill-over between industry sectors • Supply of raw materials to manufacture EV’s components
Economic	• The agreeableness and commitment of stakeholders in automotive industry • Feasibility of an EVs-driven transportation economy • Global policy on carbon credit
Social	• The seriousness of environmental problems in urban areas • Public perception toward public transportation system • Lack of trust in the cooperation between private enterprises

(Source: Consolidated by author).

5.4. Effective Method to Formulate and Implement EV Policy

The policy instrument that is usually employed to facilitate the adoption of EVs is the restriction in manufacturing outputs and sales of ICEVs. One of the earlier examples was the “zero-emission vehicle mandate” (ZEV), which was adopted by Californian Air Resource Board (CARB) in 1990. This program proved to be a successful instrument to encourage the development of research assets in the EV industry [114]. The results from the mandate indicated that several automotive enterprises increased their research effort on EVs and related technologies. However, the mandate ultimately failed to increase the sales of electric vehicles in the period that this policy was active. It was suggested that ZEV, as an exclusively technology-push mandate, was unable to influence the full range of the EV supply chain because of the shortage in demand stimulation for the EV market [11]. Therefore, it can be concluded that the government should provide supporting policies which are directed at the EV market, in addition to the regulations that are aimed to increase EV research and production output. In conclusion, every aspect of the industry should be investigated prior to the formulation of public policy. Accurate and updated information from stakeholders should be extracted via systematic methods. Then, this information could be used to enhance the potential impacts of the formulated policy.

It is recommended that an exclusive policy plan for the adoption of EVs in Thailand should be formulated by a systematic framework. In addition, this framework should be designed with the assumption that the EV industry is a complex system. The importance of a complex system framework has been mentioned by the study in the development of a knowledge, innovation, and technology cluster (KNIT). This cluster was described as the formation of internal collaborations between several elements within the network of actors [115]. Nonetheless, the scope of a KNIT cluster is considerably smaller and focuses on the aspect of internal collaborations. In contrast, the coverage of national-level policy would likely contain a significant amount of external linkage outside the system, e.g., EV emission standards for manufacturers (inside the EV industry) and department of pollution control (outside the EV industry). It was stated that innovation hardly comes from the sole effort of research and development activities because the transformation from scientific knowledge into commercialized technology would also require a commercial and managerial skillset [92]. As a result, every component in the system has to function together in a cohesive manner, both technically and socially [116]. It can be expected that the search for an effective method to formulate and implement public policy for nationwide adoption of EVs would be one of the most challenging prospects for Thai policy-makers to accomplish.

6. Conclusions

The adoption of electric vehicles (EVs) in an actual transportation system might appear as one of the distant technology-intensive targets for Thailand. However, there are many indicators from the statistics and literature that this adoption would provide substantial benefits to the national economy. Several potential impacts from the adoption of EVs were explored in this paper. It is generally accepted that the increment in EVs usage would lead to the reduction in air pollution and energy consumption for Thailand. Additionally, EVs also complement other technologies in vehicle development such as autonomous driving systems and vehicle connectivity, which would be contributory toward the improvement of road safety and the reduction of traffic congestion. On the other hand, the growth of the global market in EVs could also be considered a risky prospect for the Thai automotive industry, which is heavily devoted to internal combustion engine vehicles (ICEVs). The large amount of export value from this industry could be disrupted by this potential technological revolution. Preparation for the transition of the domestic automotive supply chain toward the new form of manufacturing process and internal economy should be made as a failsafe plan to minimize the potential negative impacts that could occur.

The main challenge for the formulation of public policy regarding the transition to electric vehicles is the disparity between supply and demand in the EV industry. In addition, there are several barriers for policy-makers to consider, such as distinctive characteristics of EVs. The pricing and technical performance of EVs still have a sizable gap when compared to ICEVs, which prevent them from being adopted by the public. In addition, the issue of confidence in new technology should also be addressed. The solution for the lack of user's confidence includes the preparation of necessary charging infrastructure, and the mechanism for Thai manufacturers to absorb EV-related technological capabilities. It is suggested that public policy should be systematically formulated by applying updated information that covers the whole range of the automotive supply chain. The successful adoption of EVs throughout the country would depend on the governmental support for both technological and market development.

It is important to acknowledge the negative effect of the global pandemic situation from coronavirus during 2020 to 2022, which reduced the amount of primary information that were collected in the data collection process. Improvement to the results can be expected from additional collection of primary data in Thailand. Moreover, the pandemic situation also negatively affected the overall progress in the EV industry within Thailand. This circumstance might warrant the revision of some changes in the national policy plan which could affect the overall situation of EVs technical development and EVs market in the country. Several improvements could be made for future research that would be based on this paper. For example, the author is currently developing a thesis regarding the development of electric vehicle's governmental policy based on the information that has been outlined in this paper.

Author Contributions: Conceptualization, K.P., D.B. and J.M.; Methodology, K.P. and D.B.; Validation, K.P. and D.B.; Formal analysis, K.P.; Investigation, K.P.; Data curation, K.P.; Writing—original draft preparation, K.P.; Writing—review and editing, K.P., D.B. and J.M.; Visualization, K.P.; Supervision, D.B. and J.M.; Project administration, D.B. and J.M.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding, and the APC was funded by University of Strathclyde open access program.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the data collection process, primarily involving several interviews. The interviews as a method for data collection is waived based on local research authority as long as they do not contain sensitive and personal information that put the respondents at risk.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the inclusive business-related sensitive information. This included the transcription of interviews that were conducted for this research.

Acknowledgments: I would like to express my thanks to the Office of National Higher Education Science Research and Innovation Policy Council (NXPO) for providing me a valuable opportunity to study in a post-graduate research program at the University of Strathclyde.

Conflicts of Interest: The authors declare no conflict of interest with regard to the publication of this article.

References

1. Muratori, M.; Mai, T. The shape of electrified transportation. *Environ. Res. Lett.* **2020**, *16*, 011003. [CrossRef]
2. Høyer, K.G. The history of alternative fuels in transportation: The case of electric and hybrid cars. *Util. Policy* **2008**, *16*, 63–71. [CrossRef]
3. Cutcliffe, S.H.; Kirsch, D.A. The Electric Vehicle and the Burden of History. *Environ. Hist.* **2001**, *6*, 326–328. [CrossRef]
4. Kancherla, Y.D.; Daim, T.U. Technology Roadmap: A Roadmap for Tesla. In *Infrastructure and Technology Management*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 347–366.
5. Newbery, D.; Strbac, G. What is needed for battery electric vehicles to become socially cost competitive? *Econ. Transp.* **2016**, *5*, 1–11. [CrossRef]
6. Machol, B.; Rizk, S. Economic value of U.S. fossil fuel electricity health impacts. *Environ. Int.* **2013**, *52*, 75–80. [CrossRef]
7. Qiao, Q.; Zhao, F.; Liu, Z.; Hao, H.; He, X.; Przesmitzki, S.V.; Amer, A.A. Life cycle cost and GHG emission benefits of electric vehicles in China. *Transp. Res. Part D Transp. Environ.* **2020**, *86*, 102418. [CrossRef]
8. Xiaoyan, H. Research on the evolution mechanism of the electric vehicle market driven by big data. *Concurr. Comput. Pract. Exp.* **2019**, *32*, e5148. [CrossRef]
9. Collantes, G.; Sperling, D. The origin of California's zero emission vehicle mandate. *Transp. Res. Part A: Policy Pract.* **2008**, *42*, 1302–1313. [CrossRef]
10. Greene, D.L.; Park, S.; Liu, C. Public policy and the transition to electric drive vehicles in the U.S.: The role of the zero emission vehicles mandates. *Energy Strat. Rev.* **2014**, *5*, 66–77. [CrossRef]
11. Kemp, R. *Zero Emission Vehicle Mandate in California: Misguided Policy or Example of Enlightened Leadership*; Edward Elgar: Cheltenham, UK, 2005.
12. *The Number of Newly Registered Electric Vehicles in Thailand by Types*; Thailand Automotive Institue, Ministry of Industry: Bangkok, Thailand, 2022.
13. *The Total Amount of EV Charging Stations in Thailand as of 2022*; Energy Policy and Planning Office, Ministry of Energy: Bangkok, Thailand, 2022.
14. Kvaløy, B.; Finseraas, H.; Listhaug, O. The publics' concern for global warming: A cross-national study of 47 countries. *J. Peace Res.* **2012**, *49*, 11–22. [CrossRef]
15. Wu, Y.; Zhang, L. Can the development of electric vehicles reduce the emission of air pollutants and greenhouse gases in developing countries? *Transp. Res. Part D Transp. Environ.* **2017**, *51*, 129–145. [CrossRef]
16. *Proportion of Energy Types Used in the Generation of Electricity of the Country*; Electricity Generating Authority of Thailand, Ministry of Energy: Bangkok, Thailand, 2020.
17. Massamadon, R. Policies and drivers for the adoption of electric vehicles in Thailand. In Proceedings of the Future of Electric Vehicles in Thailand, Grand Miracle Hotel, Bangkok, Thailand, 17 August 2020.
18. Prateep, C.; Navadol, L.; Somchai, C.; Chumnong, S.; Withaya, Y. Economical and environmental assessments of compressed natural gas for diesel vehicle in Thailand. *Wārasān Songkhlā Nakharin* **2008**, *30*, 747–754.
19. The emission of diesel vehicles and PM2.5. In Proceedings of the Impacts of Electric Vehicles Adoption on Fine Particulate Matter (PM2.5) Pollution Problem in Bangkok, Bangkok, Thailand, 29 July 2020; The Parliament of Thailand: Bangkok, Thailand.
20. Gray, G. *Remanufacture, refurbishment, reuse and recycling of vehicles: Trends and opportunities*; APS Group: Scotland, UK, 2013.
21. Sevinc, V.; Kucuk, O.; Göltaş, M. A Bayesian network model for prediction and analysis of possible forest fire causes. *For. Ecol. Manag.* **2020**, *457*, 117723. [CrossRef]
22. Kaushal, L.A.; Prashar, A. Agricultural crop residue burning and its environmental impacts and potential causes—Case of northwest India. *J. Environ. Plan. Manag.* **2020**, *64*, 464–484. [CrossRef]
23. Choi, D.G.; Kreikebaum, F.; Thomas, V.M.; Divan, D. Coordinated EV Adoption: Double-Digit Reductions in Emissions and Fuel Use for $40/Vehicle-Year. *Environ. Sci. Technol.* **2013**, *47*, 10703–10707. [CrossRef] [PubMed]

24. *Thailand's Crude Oil Imports 2011–2020*; Ministry of Energy: Bangkok, Thailand, 2021.
25. Alsharif, A.; Tan, C.W.; Ayop, R.; Dobi, A.; Lau, K.Y. A comprehensive review of energy management strategy in Vehicle-to-Grid technology integrated with renewable energy sources. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101439. [CrossRef]
26. Rentizelas, A.; Tolis, A.; Tatsiopoulos, I.P. Investment planning in electricity production under CO_2 price uncertainty. *Int. J. Prod. Econ.* **2012**, *140*, 622–629. [CrossRef]
27. Uthathip, N.; Bhasaputra, P.; Pattaraprakorn, W. Stochastic Modelling to Analyze the Impact of Electric Vehicle Penetration in Thailand. *Energies* **2021**, *14*, 5037. [CrossRef]
28. Terán, M.V.; Center, P.D. Philosophical Explorations for a Concept of Emerging Technologies. *Techne: Res. Philos. Technol.* **2018**, *22*, 28–50. [CrossRef]
29. Markides, C. Disruptive Innovation: In Need of Better Theory. *J. Prod. Innov. Manag.* **2006**, *23*, 19–25. [CrossRef]
30. King, A.A.; Baatartogtokh, B. How useful is the theory of disruptive innovation? *MIT Sloan Manag. Rev.* **2015**, *57*, 77.
31. Hardman, S.; Steinberger-Wilckens, R.; van der Horst, D. Disruptive innovations: The case for hydrogen fuel cells and battery electric vehicles. *Int. J. Hydrogen Energy* **2013**, *38*, 15438–15451. [CrossRef]
32. Mohamad, M.; Songthaveephol, V. Clash of titans: The challenges of socio-technical transitions in the electrical vehicle technologies—The case study of Thai automotive industry. *Technol. Forecast. Soc. Chang.* **2020**, *153*, 119772. [CrossRef]
33. Upadhyay, A.; Dalal, M.; Sanghvi, N.; Singh, V.; Nair, S.; Scurtu, I.C.; Dragan, C. Electric Vehicles over Contemporary Combustion Engines. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *635*, 012004. [CrossRef]
34. Bell, J.F.; Monaco, L. Power and supply chain development in the South African and Thai automotive industries: What lessons can be learnt? *J. Int. Dev.* **2021**, *33*, 457–471. [CrossRef]
35. Schröder, M. Electric vehicle policy in Thailand: Limitations of product champions. *J. Asia Pac. Econ.* **2021**, 1–26. [CrossRef]
36. Junquera, B.; Moreno, B.; Álvarez, R. Analyzing consumer attitudes towards electric vehicle purchasing intentions in Spain: Technological limitations and vehicle confidence. *Technol. Forecast. Soc. Chang.* **2016**, *109*, 6–14. [CrossRef]
37. Lee, C.-H.; Wu, C.-H. Learning To Recognize Driving Patterns For Collectively Characterizing Electric Vehicle Driving Behaviors. *Int. J. Automot. Technol.* **2019**, *20*, 1263–1276. [CrossRef]
38. Lucas, A.; Barranco, R.; Refa, N. EV Idle Time Estimation on Charging Infrastructure, Comparing Supervised Machine Learning Regressions. *Energies* **2019**, *12*, 269. [CrossRef]
39. Zhang, B.; Niu, N.; Li, H.; Wang, Z.; He, W. Could fast battery charging effectively mitigate range anxiety in electric vehicle usage?Evidence from large-scale data on travel and charging in Beijing. *Transp. Res. Part D Transp. Environ.* **2021**, *95*, 102840. [CrossRef]
40. Zhu, G.; Zhao, C.; Huang, J.; He, C.; Zhang, J.; Chen, S.; Xu, L.; Yuan, H.; Zhang, Q. Fast Charging Lithium Batteries: Recent Progress and Future Prospects. *Small* **2019**, *15*, e1805389. [CrossRef]
41. Lorentzen, E.; Haugneland, P.; Bu, C.; Hauge, E. Charging infrastructure experiences in Norway-the worlds most advanced EV market. In Proceedings of the EVS30 Symposium, Stuttgart, Germany, 9–11 October 2017.
42. Philipsen, R.; Schmidt, T.; Van Heek, J.; Ziefle, M. Fast-charging station here, please! User criteria for electric vehicle fast-charging locations. *Transp. Res. Part F Traffic Psychol. Behav.* **2016**, *40*, 119–129. [CrossRef]
43. Thananusak, T.; Rakthin, S.; Tavewatanaphan, T.; Punnakitikashem, P. Factors affecting the intention to buy electric vehicles: Empirical evidence from Thailand. *Int. J. Electr. Hybrid Veh.* **2017**, *9*, 361–381. [CrossRef]
44. Hidrue, M.K.; Parsons, G.R.; Kempton, W.; Gardner, M.P. Willingness to pay for electric vehicles and their attributes. *Resour. Energy Econ.* **2011**, *33*, 686–705. [CrossRef]
45. Lin, B.; Wu, W. Why people want to buy electric vehicle: An empirical study in first-tier cities of China. *Energy Policy* **2018**, *112*, 233–241. [CrossRef]
46. Gu, H.; Liu, Z.; Qing, Q. Optimal electric vehicle production strategy under subsidy and battery recycling. *Energy Policy* **2017**, *109*, 579–589. [CrossRef]
47. Palmer, K.; Tate, J.E.; Wadud, Z.; Nellthorp, J. Total cost of ownership and market share for hybrid and electric vehicles in the UK, US and Japan. *Appl. Energy* **2018**, *209*, 108–119. [CrossRef]
48. Al-Alawi, B.M.; Bradley, T.H. Total cost of ownership, payback, and consumer preference modeling of plug-in hybrid electric vehicles. *Appl. Energy* **2013**, *103*, 488–506. [CrossRef]
49. Gass, V.; Schmidt, J.; Schmid, E. Analysis of alternative policy instruments to promote electric vehicles in Austria. *Renew. Energy* **2014**, *61*, 96–101. [CrossRef]
50. Kester, J.; Noel, L.; de Rubens, G.Z.; Sovacool, B.K. Policy mechanisms to accelerate electric vehicle adoption: A qualitative review from the Nordic region. *Renew. Sustain. Energy Rev.* **2018**, *94*, 719–731. [CrossRef]
51. Hagman, J.; Ritzén, S.; Stier, J.J.; Susilo, Y. Total cost of ownership and its potential implications for battery electric vehicle diffusion. *Res. Transp. Bus. Manag.* **2016**, *18*, 11–17. [CrossRef]
52. Adler, M.; Peer, S.; Sinozic, T. Autonomous, connected, electric shared vehicles (ACES) and public finance: An explorative analysis. *Transp. Res. Interdiscip. Perspect.* **2019**, *2*, 100038. [CrossRef]
53. Popov, N.S.; Anosov, V.N.; E Vilberger, M.; A Domakhin, E.; I Anibroev, V.; I Singizin, I. Development of autonomous traction system of electric vehicle with electronic differential and fuzzy control system. *J. Physics Conf. Ser.* **2020**, *1661*, 012108. [CrossRef]
54. Burd, J.T.J.; Moore, E.A.; Ezzat, H.; Kirchain, R.; Roth, R. Improvements in electric vehicle battery technology influence vehicle lightweighting and material substitution decisions. *Appl. Energy* **2021**, *283*, 116269. [CrossRef]

55. Ye, L.; Yamamoto, T. Evaluating the impact of connected and autonomous vehicles on traffic safety. *Phys. A Stat. Mech. Its Appl.* **2019**, *526*, 121009. [CrossRef]
56. Mahmood, Z. *Connected Vehicles in the Internet of Things: Concepts, Technologies and Frameworks for the IoV.*; Springer International Publishing AG: Cham, Switzerland, 2020. [CrossRef]
57. Mohsen, M. Sharing or owning autonomous vehicles? Comprehending the role of ideology in the adoption of autonomous vehicles in the society of automobility. *Transp. Res. Interdiscip. Perspect.* **2021**, *9*, 100294.
58. Economic Loss from Traffic Congestion in Bangkok. Available online: https://www.posttoday.com/politic/analysis/453653 (accessed on 1 September 2022).
59. Friman, M.; Larhult, L.; Gärling, T. An analysis of soft transport policy measures implemented in Sweden to reduce private car use. *Transportation* **2013**, *40*, 109–129. [CrossRef]
60. Ivanco, A. Fleet analysis of headway distance for autonomous driving. *J. Saf. Res.* **2017**, *63*, 145–148. [CrossRef]
61. Fayazi, S.A.; Vahidi, A.; Luckow, A. A Vehicle-in-the-Loop (VIL) verification of an all-autonomous intersection control scheme. *Transp. Res. Part C Emerg. Technol.* **2019**, *107*, 193–210. [CrossRef]
62. Cheewapattananuwong, W. Thailand Ranks Second in the World for Number of Road Accidents under Thailand's Codes of Geometrical Design and Traffic Engineering Concept When Compared with AASHTO. *MATEC Web Conf.* **2016**, *81*, 02004. [CrossRef]
63. Jomnonkwao, S.; Uttra, S.; Ratanavaraha, V. Forecasting Road Traffic Deaths in Thailand: Applications of Time-Series, Curve Estimation, Multiple Linear Regression, and Path Analysis Models. *Sustainability* **2020**, *12*, 395. [CrossRef]
64. Chaturaphat, C.; Chompoonuh, K.P.; Bertrand, H. Measure of productivity loss due to road traffic accidents in Thailand. *IATSS Res.* **2021**, *45*, 131–136.
65. Chipka, J.B.; Campbell, M. Estimation and navigation methods with limited information for autonomous urban driving. *Eng. Rep.* **2019**, *1*, e12054. [CrossRef]
66. Massier, T.; Recalde, D.; Sellmair, R.; Gallet, M.; Hamacher, T. Electrification of Road Transport in Singapore and its Integration into the Power System. *Energy Technol.* **2018**, *6*, 21–32. [CrossRef]
67. Li, Y.; Kochhan, R. Policies and Business Models for the Electric Mobility Revolution: The Case Study on Singapore. *Singap. Econ. Rev.* **2017**, *62*, 1195–1222. [CrossRef]
68. Olszewski, P.S. Singapore motorisation restraint and its implications on travel behaviour and urban sustainability. *Transportation* **2007**, *34*, 319–335. [CrossRef]
69. Brinkmann, D.; Bhatiasevi, V. Purchase Intention for Electric Vehicles Among Young Adults in Thailand. *Vision* **2021**, 09722629211001981. [CrossRef]
70. Wongdeethai, T. *Future of EV Policy in Thailand*; Interviewed by Kantapich Preedakorn: Bangkok, Thailand, 2019.
71. Narakornphaijitr, P. *Opinions of Operators on E-Bus compared to ICE-Bus or NGV-Bus*, Interviewed by Kantapich Preedakorn, Bangkok, Thailand. 2020.
72. Egbue, O.; Long, S. Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions. *Energy Policy* **2012**, *48*, 717–729. [CrossRef]
73. Beaume, R.; Midler, C. From technology competition to reinventing individual ecomobility: New design strategies for electric vehicles. *Int. J. Automot. Technol. Manag.* **2009**, *9*, 174. [CrossRef]
74. Bonges, H.A.; Lusk, A.C. Addressing electric vehicle (EV) sales and range anxiety through parking layout, policy and regulation. *Transp. Res. Part A Policy Pract.* **2016**, *83*, 63–73. [CrossRef]
75. Hardman, S.; Shiu, E.; Steinberger-Wilckens, R. Changing the fate of Fuel Cell Vehicles: Can lessons be learnt from Tesla Motors? *Int. J. Hydrogen Energy* **2015**, *40*, 1625–1638. [CrossRef]
76. Cowan, R.; Hultén, S. Escaping lock-in: The case of the electric vehicle. *Technol. Forecast. Soc. Chang.* **1996**, *53*, 61–79. [CrossRef]
77. Hildermeier, J.; Villareal, A. Shaping an emerging market for electric cars: How politics in France and Germany transform the European automotive industry. *Eur. Rev. Ind. Econ. Policy*. 2011, 3. Available online: https://hal.archives-ouvertes.fr/halshs-00677752 (accessed on 1 September 2022).
78. Semelsberger, T.A.; Borup, R.L.; Greene, H.L. Dimethyl ether (DME) as an alternative fuel. *J. Power Sources* **2006**, *156*, 497–511. [CrossRef]
79. Jalihal, S.A.; Reddy, T.S. CNG: An alternative fuel for public transport. *J. Sci. Ind. Res.* **2006**, *65*, 426–431.
80. Valera, H.; Agarwal, A.K. Methanol as an alternative fuel for diesel engines. In *Methanol and the Alternate Fuel Economy*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 9–33.
81. Long, Z.; Axsen, J.; Kormos, C. Consumers continue to be confused about electric vehicles: Comparing awareness among Canadian new car buyers in 2013 and 2017. *Environ. Res. Lett.* **2019**, *14*, 114036. [CrossRef]
82. Lorentz, H.; Hilmola, O.-P. Confidence and supply chain disruptions: Insights into managerial decision-making from the perspective of policy. *J. Model. Manag.* **2012**, *7*, 328–356. [CrossRef]
83. Laoonual, Y. *The current situation of EV and e-bus industry in Thailand*, Interviewed by Kantapich Preedakorn: Bangkok, Thailand. 2020.
84. Wanichanukul, S. *Technological capabilities of Thai auto industry and the opportunities in the transition toward electric vehicles ecosystem*, Interviewed by Kantapich Preedakorn, Bangkok, Thailand. 2020.

85. Intarakumnerd, P.; Techakanont, K. Intra-industry trade, product fragmentation and technological capability development in Thai automotive industry. *Asia Pac. Bus. Rev.* **2016**, *22*, 65–85. [CrossRef]
86. Yoon, D. The regional-innovation cluster policy for R&D efficiency and the creative economy. *J. Sci. Technol. Policy Manag.* **2017**, *8*, 206–226. [CrossRef]
87. Hegde, D.; Shapira, P. Knowledge, technology trajectories, and innovation in a developing country context: Evidence from a survey of Malaysian firms. *Int. J. Technol. Manag.* **2007**, *40*, 349–370. [CrossRef]
88. Agarwal, R.; Audretsch, D.B. Does Entry Size Matter? The Impact of the Life Cycle and Technology on Firm Survival. *J. Ind. Econ.* **2001**, *49*, 21–43. [CrossRef]
89. Suebsupanand, P. *Manufacturer's Point of View on e-Bus National Policy and Industry Researches*; Interviewed by Kantapich Preedakorn: Bangkok, Thailand, 2020.
90. Cherdchai, S. *Feasibility and Profitability of E-bus Manufacturing Industry*; Interviewed by Kantapich Preedakorn: Bangkok, Thailand, 2020.
91. Ladyman, J.; Lambert, J.; Wiesner, K. What is a complex system? *Eur. J. Philos. Sci.* **2013**, *3*, 33–67. [CrossRef]
92. Mastroeni, M.; Omidvar, O.; Rosiello, A.; Tait, J.; Wield, D. Science and innovation dynamics and policy in Scotland: The perceived impact of enhanced autonomy. *Int. J. Technol. Manag. Sustain. Dev.* **2017**, *16*, 3–24. [CrossRef] [PubMed]
93. Wonglimpiyarat, J. Strategic management of industrial clusters in Thailand. *Innovation* **2006**, *8*, 273–287. [CrossRef]
94. Salvador, E.; Mariotti, I.; Conicella, F. Science park or innovation cluster? *Int. J. Entrep. Behav. Res.* **2013**, *19*, 656–674. [CrossRef]
95. Quintas, P.; Wield, D.; Massey, D. Academic-industry links and innovation: Questioning the science park model. *Technovation* **1992**, *12*, 161–175. [CrossRef]
96. Lee, W.; Choi, J.-I. Industry-academia cooperation in creative innovation clusters: A comparison of two clusters in Korea. *Acad. Entrep. J.* **2013**, *19*, 79.
97. Liao, S.-H.; Fei, W.-C.; Chen, C.-C. Knowledge sharing, absorptive capacity, and innovation capability: An empirical study of Taiwan's knowledge-intensive industries. *J. Inf. Sci.* **2007**, *33*, 340–359. [CrossRef]
98. Engel, J.S. Global Clusters of Innovation: Lessons from Silicon Valley. *Calif. Manag. Rev.* **2015**, *57*, 36–65. [CrossRef]
99. Dong, X.; Hu, Y.; Yin, W.; Kuo, E. *Zhongguancun Model: Driving the Dual Engines of Science & Technology and Capital*; Springer: Singapore, 2018.
100. Lenchuk, E.B.; Vlaskin, G.A. The cluster approach in the innovation development strategy of foreign countries. *Stud. Russ. Econ. Dev.* **2010**, *21*, 484–492. [CrossRef]
101. Jucevičius, G.; Grumadaitė, K. Smart development of innovation ecosystem. *Procedia-Soc. Behav. Sci.* **2014**, *156*, 125–129. [CrossRef]
102. Filho, M.F.; Heerdt, M.L. Innovation Emergence: Public Policies versus Actors' Free Interaction. *Systems* **2018**, *6*, 13. [CrossRef]
103. Strumpf, K.S. Does government decentralization increase policy innovation? *J. Public Econ. Theory* **2002**, *4*, 207–241. [CrossRef]
104. Fromhold-Eisebith, M.; Eisebith, G. How to institutionalize innovative clusters? Comparing explicit top-down and implicit bottom-up approaches. *Res. Policy* **2005**, *34*, 1250–1268. [CrossRef]
105. Goswami, A.G. Vertical FDI versus outsourcing: The role of technology transfer costs. *N. Am. J. Econ. Finance* **2013**, *25*, 1–21. [CrossRef]
106. Amesse, F.; Cohendet, P. Technology transfer revisited from the perspective of the knowledge-based economy. *Res. Policy* **2001**, *30*, 1459–1478. [CrossRef]
107. Barson, R.J.; Foster, G.; Struck, T.; Ratchev, S.; Pawar, K.; Weber, F.; Wunram, M. Inter-and intra-organisational barriers to sharing knowledge in the extended supply-chain. In Proceedings of the eBusiness and eWork; 2000; pp. 18–20. Available online: https://www.academia.edu/19118250/Inter_and_intra_Organisational_barriers_to_sharing_knowledge_in_the_extended_supply_chain (accessed on 6 August 2021).
108. Johnston, M. 5 Companies Owned by Tesla. Available online: https://www.investopedia.com/companies-owned-by-tesla-5092764 (accessed on 22 February 2022).
109. Galatoulas, N.-F.; Genikomsakis, K.N.; Ioakimidis, C.S. Analysis of potential demand and costs for the business development of an electric vehicle sharing service. *Sustain. Cities Soc.* **2018**, *42*, 148–161. [CrossRef]
110. Holtsmark, B.; Skonhoft, A. The Norwegian support and subsidy policy of electric cars. Should it be adopted by other countries? *Environ. Sci. Policy* **2014**, *42*, 160–168. [CrossRef]
111. Nilsson, M.; Nykvist, B. Governing the electric vehicle transition—Near term interventions to support a green energy economy. *Appl. Energy* **2016**, *179*, 1360–1371. [CrossRef]
112. Morton, C.; Anable, J.; Brand, C. Policy making under uncertainty in electric vehicle demand. *Proc. Inst. Civ. Eng.-Energy* **2014**, *167*, 125–138. [CrossRef]
113. Dyerson, R.; Pilkington, A. Innovation in complex systems: Regulation and technology towards the electric vehicle. *Int. J. Innov. Manag.* **2000**, *4*, 33–49. [CrossRef]
114. Wesseling, J.H.; Niesten, E.M.M.I.; Faber, J.; Hekkert, M.P. Business Strategies of Incumbents in the Market for Electric Vehicles: Opportunities and Incentives for Sustainable Innovation. *Bus. Strat. Environ.* **2015**, *24*, 518–531. [CrossRef]

115. Rutkauskas, A.V.; Račinskaja, I.; Kvietkauskienė, A. Integrated knowledge, innovation and technology cluster as a self-regulating complex system. *Bus. Manag. Econ. Eng.* **2013**, *11*, 294–314. [CrossRef]
116. Lundvall, B.-Å. *Innovation, Growth, and Social Cohesion: The Danish Model*; Edward Elgar Publishing: Cheltenham, UK, 2002.