LUND UNIVERSITY
School of Economics and Management

Master programme in Innovation and Spatial Dynamics

Innovation policy for the promotion of electric vehicles in developed countries (Japan, Sweden, and Germany)

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Abstract: Though the diffusion of electric vehicle (EV) is high on the global agenda, and there are efforts to speed up the shift: some countries intend to ban the sale of internal combustion engine vehicles (ICEV), and some OEMs (original equipment manufacturers) have announced the goal of electrification, the diffusion of EV is slowly. Technological innovation theory explains that we need to harmonise technological development, socio-technical reconfiguration, and social movement for a technological transition, and especially in the case of carbon-saving technology, the destabilization of the socio-technical regime is crucial to the transition (Geels, 2002, 2014). Additionally, some studies emphasise the importance of shifting OEMs' business strategies (Kieckhäfer et al, 2017). In this thesis, I give an overview of the barriers to EV promotion structurally reflecting these theories and the present situation, and then analyse ways of diffusing and the governmental role in this process, especially in Japan, Sweden, and Germany, countries famous for their automobile industries. I collect some time series data about EV assets for OEMs and then examine the relationship between the data and the latest regulation trends in global. I also conduct interviews with OEMs and policy. Through the data analysis and interviews, I find that the trend of regulations today has affected the increase in EV assets and the shift of OEMs' strategies to electrification, and that regulations which give OEMs an incentive to pursue EV development are crucial to the technological transition from ICEV to EVs

Key words: EV, electric vehicle, technological transition, technological innovation, innovation policy, socio-technical regime

EKHS31
Master thesis, First Year (15 credits ECTS)
June 2018
Supervisor: Hana Nielsen
Examiner: Jonas Ljungberg
Word Count: 13,809

Acknowledgements

I would like to express my gratitude to my supervisor Hana Nielsen and co-supervisor Viktoras Kulionis for providing me with valuable comments and leading me to finish writing thesis. Without their help, I would not finish publishing this thesis. And I am also thankful to all the interviewee who were willing to take my interview although they had a lot of task.

I am also sincerely grateful to my family for supporting me anytime.

Jiro Arai 30st of May 2018[1]

[1] The views and opinions expressed herein are those of the author and do not necessarily reflect the views of the organization the author belongs to.

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1 Introduction

In many developed countries and China, governments and OEMs (original equipment manufacturers, i.e. automobile companies like VW, Toyota, or GM) have announced a shift to EV (electric vehicle, e.g. the Tesla model S, Nissan Leaf, or BMW i3) from ICEV (internal combustion engine vehicle, i.e. car driven by diesel or gasoline engines). The aim of the shift is driven by environmental issues. For example, the amount of CO2 emitted by automobiles accounts for about 15% of total CO2 emissions in the EU (EU, 2017a, online). And toxic gases like NOx and PM emitted from cars harm human health, especially in cities. Though the shift is an important way to reduce emissions and many governments have pursued policies to encourage it for a long time, the speed of the transformation is slow.

In terms of demand, the EV market is dependent on political support and otherwise limited to luxury markets. Indeed, some people are eager to purchase EV as an eco-friendly product, but so far, EVs can be described as a niche market highly dependent on government support, or as luxury cars like Tesla, thus it is said that in order to increase sales of EV, governmental incentives are important (Rong et al., 2017). In fact, IEA (international energy agency) argues that EV sales depend on financial incentives from governments (IEA, 2017a). IEA argues that EV sales in Denmark decreased in 2016 compared to 2015, and this drop was caused by the reduction of incentive policies. In the same period, the policy change also caused a decrease in the sales of Tesla luxury EVs, from 2,736 to 176 (Database of Marklines).

In terms of supply, the sales of EV and PHEV (plug-in hybrid vehicle) is about 1.1% of total annual car sales in the major EV markets (IEA, 2017a), and the speed is slower than we expected. I take an example, the case for Nissan, which has been the top EV seller in the world since it first started to sell EVs in global markets 2010. In April 2018, Nissan announced that the total sales of its EV 'LEAF' reached over 320,000 globally (Nissan, 2018a). However, this number is far smaller than the target Nissan set in June 2011 at 1,500,000 by the 2016 fiscal year (Nissan, 2011).

Thus, it is important how innovation surrounding the development of EVs and their faster take-off can be generated and implemented. EVs have almost the same history as ICEVs (both vehicles developed during the twentieth century), so the concept of cars driven by electricity is not new (Cowan and Hultén, 1996). However, the commercialisation of EVs is much more limited than that of ICEVs, thus we need to understand more how it is possible to further promote innovation around EVs. This innovation is important for addressing such global concerns as global warming and sustainable life in cities, because in contrast to ICEVs, EVs do not emit exhaust gas, and therefore contribute to reductions in the amount of CO2 and improve air conditions in cities.

There are many potential fields of innovation related to EVs. For example, the development of batteries will lead to price decreases and increases in the driving range of the vehicles, and development of charging technologies will improve consumer satisfaction. These technological innovations are regarded as the key factors in encouraging consumer interest in EVs (Egbue and Long, 2012). However, we need to take into consideration not only these technological parameters, but also the structural problems preventing EV market penetration. What makes EV promotion difficult is that it disrupts the existing institutional structure, which is based on ICEVs and fossil fuels (Unruh, 2000). For instance, some reports argue that the shift from ICEVs to EVs will cause job destruction in automobile industries (Economist, 2018; IFO, 2017). And the destruction will not only affect infrastructure like gas stations and oil industries; it will spread to suppliers which relate to manufacturing any of the 100,000 components used in ICEV construction. It will happen especially in the countries where many OEMs and suppliers exist. For example, 10% of workers in Japan are engaged in some respect within the activities of the automobile industry (including gas stations, dealers, etc.; METI, 2015 online). And the German Association of the Automotive Industry (VDA) argues that if governments ban the sale of ICEVs by 2030, more than 600,000 employees in Germany would lose their jobs (Reuters, 2018, online).

In the research field of innovation theory, especially technological innovation theories, much of the literature explores the general condition of promoting innovation, and the difficulties related to shifting technological regimes which strongly relate to institutional structures. For example, Geels (2002) analyses technological transition from a multi-level perspective, focusing not only on technological development but also on social movements and institutions. However, few studies have so far adapted these technological innovation theories to the case of EVs. And there are some studies that focus on the relationship between consumers and governments, such as the analysis of an effective policy incentive to consumers, and between OEMs and consumers, such as the analysis of how OEMSs' sales portfolio affects the purchasing activity of consumers, but there are few studies that have so far focues on the relationship between governments and OEMs.

Thus, this thesis aims to provide a theoretical discussion of how to promote innovation during the technological transition from ICEVs- and fossil fuel-based societies to EV-based societies, and what constitutes governments' role in this process, especially focusing on the relationship between governments and OEMs. It will reflect previous research while addressing contemporary problems. To be specific, in the last half a decade, many governments have announced and updated regulations, and many OEMs have started to announce their strategies about electrification including EV, thus I will research how the regulations have affected the OEM's strategies through a data analysis on the change of OEM's EV assets and interviews to OEMs and policy makers. I am expecting that I will verify that the effective innovation policy for promoting EVs is legislating aggressive regulations for OEMs so that governments incentivise them the development of EVs.

The remainder of this thesis is structured as follows. In the next section, I will review previous studies of technological innovation theories and barriers to EV promotion. The third section will construct a structural overview of the obstacles to the technological shift to EVs, based on technological innovation theory, and set the research question and methodology. In the fourth section, I will explore data related to the research question. The data consists of time series data of OEM's EV assets (a number of patents, and a ratio of prototypes of EVs at international auto shows), and interviews with OEMs and policymakers. In the last section, I will conclude this paper and give suggestions for further research directions.

2 Literature/theoretical Review

In this chapter, I will refer two strands of literatures so that I review previous studies of technological innovation theories and barriers to EV promotion. The first strand is technological innovation theories that do not specifically focus on EVs, but suggest general barriers to the technological transitions. The second strand is the literatures analysing the promotion EVs that show some barriers to diffuse EVs into markets. I will raise three barriers respectively as Table 2.1 shows, and I will discuss them one by one as follows.

Table 2.1 The barriers to diffuse EV

		Barriers	Proposed by
Technological Innovation Theories	1	Low production volume and productivity	Perez (2010)
	2	Established technological network based on ICEVs and fossil fuels	Unruh (2000)
	3	Malfunctions related to evolutionary reconfiguration processes with multi-level perspective	Geels (2002,2014)
Literatures analyzing the promotion of EV	4	Need for further construction of charging infrastructure	Vassileva and Campillo (2017)
	5	Insufficient performance (high price and limited driving range)	METI (2016), Han et al. (2017)
	6	Business strategy of OEMs	Kieckhäfer et al (2017) , Wesseling et al (2015)

2.1 Technological innovation theories

When we analyse a specific case of innovation, innovation theories provide the lens through which to view the contemporary situation and show how to promote vigorous innovation in such a case. The shift from ICEVs to EVs is a technological change, so technological innovation theories are an appropriate tool for analysing the barriers hindering this change. I will discuss three theories below, and with them, three barriers to EV innovation and the expected roles for governments in addressing these barriers.

2.1.1 Barrier 1: Low production volume and productivity

Perez (2010) introduces the notion of ‘technological revolutions’ as ‘opening a vast innovation opportunity space’, and explains that new technology provides a new set of infrastructures and raises the efficiency and effectiveness of all industries and activities (Perez, 2010).

Perez also explains that innovation is the collective process and that numerous minor innovations follow any major innovation. Minor innovations are important for increasing the productivity and market growth of the major innovation, but such technology (minor innovation) only follows the major innovation after it has 'taken off': in other words, once the production volume and productivity of the major innovation have reached a crucial level (Perez, 2010).

In sum, reflected by Perez's argument, EVs have potential as a 'technological revolution' as I will explain at the next chapter, but further growth in the EV market is needed to accelerate EV innovation, including numerous minor innovations. In other words, a barrier to EV diffusion is the small production volume and low productivity (proportional to price) of EVs, and there are the cause of why the EV have not yet managed to open up for other complementary innovations.

2.1.2 Barrier 2: Established technological network based on ICEVs and fossil fuels

Some previous studies examine cases involving technologies which are environmentally friendly but which disrupt existing technologies and related businesses. Unruh (2000) has highlighted the notion of 'carbon lock-in' as an explanation for slack innovation around environmentally friendly technologies. He explains that once the primary technological network based on ICEVs and fossil fuel consumption has been set up, subsystems (e.g. component technology related to ICEV, like internal combustion engine, transmission, cleaning exhaust gas system) increase along with the primary technological network (Unruh, 2000). It is said that ICEVs with complex technical systems consists of about 100,000 components, in contrast to the 10,000 components of an EV (RIETI, 2017, online). Thus, the technological network based on ICEVs and fossil fuel, and involving many subnetworks, is a major obstacle to innovation. Unruh contends that the technological network constitutes a barrier for new technologies by creating private associations in the network, and lobbying government officials for support and preferential treatment of the existing technological network (Unruh, 2000).

As to the governmental role, Unruh also argues that government incentive in new technologies can expand the scale of the next generation technological system, and this cause increasing returns mechanisms that drive down costs and increase the reliability and accessibility of the new system (Unruh, 2000).

To conclude, the wide and strong technological network centred on ICEVs and fossil fuel has the potential to play a barrier role for EV diffusion.

2.1.3 Barrier 3: Malfunctions related to evolutionary reconfiguration processes with multi-level perspective

How can we leap from the existing technological network? Geels (2002) argues that ‘Technological transitions’ are evolutionary reconfiguration processes with multi-level perspectives (i.e. macro, meso, and micro), and the success of new technological transitions are not only governed by novelty (micro-level: e.g. development of batteries) and changes at landscape level (macro-level: e.g. the social movement to protect against global warming), but also by changes at a socio-technical regimes level (meso-level: e.g. regulation, industrial network, user practices and application domains, infrastructure) (Geels, 2002).

Geels (2014) also applies his notion of ‘technological transitions’ to low-carbon technologies. He depicts the case of the UK electricity system and shows that the existing regime is stable because power and politics underpin the development and implementation of specific policies to stabilise the regimes, and because the regime actively resists the technological and social transition. Reflecting Geels’ perspective, it seems that there are some malfunctions in multi-level harmonisation for EV promotion, and these may play the role of barriers.

He also contends that it is crucial to enact the destabilisation of existing regimes so that we can realise the low-carbon transition, and suggests that governments should pay much more attention to the destabilization and how existing fossil fuel regimes wane.

His framework of technological transitions and his suggestion of ‘destabilization’ will form the foundation for my thesis, because the purpose of my thesis is to analyse not only today’s situation but also the expected role for government in shifting technological regimes. Thus, I will return to his framework in the third chapter, which illustrates a structural overview of the problems of EV penetration.

To summarise the barriers to EV innovation derived from the three technological innovation theories, we have small production and low productivity of EV (Perez, 2010), strong technological networks around ICEVs and fossil fuels (Unruh, 2000), and malfunctions within multi-level harmonisation for EV promotion (Geels, 2002, 2014).

2.2 Literatures analysing the promotion of EVs

Before I give overview the barriers to EV market penetration from a structural standpoint in the third chapter, I will review some additional barriers that have already been discussed in previous studies focused on EVs. Thus far, reflecting today’s EV policy incentives, such as subsidies, tax reductions, and construction of charging infrastructures, a number of studies have reported the consumer attitude to EVs and the effective policy measures to incentivise purchasing EVs. From these studies that analyse the problem in depth, I will add some barriers.

2.2.1 Barrier 4: Need for further construction of charging infrastructure

Vassileva and Campillo (2017) investigate the EV owners in Sweden in 2015, to analyse demographic characteristics, their reasons for purchasing EVs, and their preference for EVs. They find that the typical owners are 'male, well-educated, and have medium-high income', that they charge their vehicles at home (Vassileva and Campillo, 2017), that they bought EVs for environmental and economic reasons, and that almost all of them are satisfied with EV performance. They argue that to create a large EV market, governments should pay attention to support for the planning of charging infrastructures in the area in which people live densely (Vassileva and Campillo, 2017). The need for further construction of charging stations are also pointed out by other studies (Wang et al., 2017; Rong et al., 2017).

2.2.2 Barrier 5: Insufficient performance (high price and limited driving range)

The Japanese government published a roadmap for EV promotion in 2016, and in addition to 'insufficient infrastructure' that I have already mentioned as barrier 4, it regarded 'high price', 'short driving range', 'low attractiveness of EV', and 'long time for charging' as the problems preventing consumers from purchasing EVs. The government therefore suggested that these problems should be addressed in order to penetrate EVs into the Japanese market. (METI, 2016)

Similar research focuses on China, the biggest EV market with generous governmental incentives. For example, Han et al. (2017) researched consumer attitudes in China, and found that the functional values of EV such as cost and driving range, as well as convenience of charging infrastructure play the dominant role in deciding whether to purchase an EV. On the other hand, non-functional values such as emotional experience and self or social identity reflected by the ownership of EVs, did not directly affect the decision. And they also mention that many respondents regard political support for EV, such as subsidies, as not being fully implemented or permanent. In fact, in 2016, the Chinese government officially commented that they were going to stop EV subsidies by 2020. Other than subsidies, the Chinese government offers some incentives for EV users, such as quicker car registration than what is available to ICEV drivers. In the study by Han et al., consumers regarded such incentives as temporary.

To conclude, in order to realise sustainable growth in the EV market without governmental support, it is necessary to improve the functional value of EVs, for example by decreasing the price and extending the driving range. That is, the expense, limited driving range, and inconvenience of charging are barriers for EV promotion.

2.2.3 Barrier 6: Business strategy of OEMs

There are also several studies that describe EV market penetration in relation to OEMs' business strategies.

Kieckhäfer et al. (2017) demonstrate the future sales of EVs in Germany with simulation models, taking into account OEMs' sales portfolio options as well as consumers' purchase decisions. They show that how many types of EV OEMs offer plays the crucial role in EV market penetration because consumers can select EV from many options and this make consumers positive to purchase EV. Thus, OEMs' business strategies in relation to EVs are a barrier to EV promotion.

About the strategies, Wesseling et al (2015) argue that EV sales rely on the incentives and opportunities for promotion provided by OEMs. If some OEMs have smaller benefit from ICEVs than competitors, the OEMs have more incentive to promote EV than the competitors in order to gain profits from future market in advance. If some OEMs have many assets about EV technologies, it means that the OEMs have more opportunities to sell EV than the other OEMs which does not have sufficient EV assets. They examine each OEMs' EV sales over the period 1990-2011, and measure their net income as incentive, and their assets data related to EVs (i.e. patents, partnerships, and prototype models present at auto shows) as opportunity. They conclude that large OEMs with both incentive and opportunity (equal to say they gain less profit, and have more EV assets than competitors in ICEVs market), tend to act progressively to increase EV sales, and they exemplify Nissan as the OEM aggressively pushing EVs (Wesseling et al, 2015). Their analytical framework and theory will form the foundation for analysing current OEMs' EV strategies, and I will return to this framework in the methodology section.

As to the expected governmental role, they suggest that governments should focus on how to steer OEMs to improve their offer of EVs, as well as how to subsidize consumers to purchase and use EVs (Kieckhäfer et al, 2017). This study is unique in that it defines the governmental role as not only to incentivise consumers, but also to push OEMs.

To summarise, the barriers from previous studies about EV are the need for further construction of charging infrastructure (Vassileva and Campillo, 2017), inadequate performance of EV (METI, 2016; Han et al., 2017), and the business strategies of OEMs (Kieckhäfer et al., 2017; Wesseling et al., 2015).

3 Structural overview of the problem, and research questions

3.1 Gaps between existing academic literatures and the current EV situation

There are three gaps between existing academic literature and the current EV situation. First, while several systematic reviews of technological innovation have been undertaken (e.g. Unruh, 2000; Perez, 2010; Geels, 2002), but up to now, there are few technological innovation theory studies that specifically focusing on EVs. Second, there were major developments related to EV market penetration in 2017, for example in China, the world's largest automobile market, where the government published a new 'NEV regulation' which will start from 2019 and impose NEV (new energy vehicles consist of EV, FCV, PHEV) sales duty on OEMs, for example the OEMs need to satisfy 10% sales of NEV in 2019. Toyota, meanwhile, announced a partnership with Japanese OEMs like Mazda to develop EVs. Previous academic literatures do not include and reflect on these significant events. Third, most research that focuses on EVs has focused on the relationship between OEMs and consumers (e.g. Kieckhäfer et al, 2017), and between consumers and governments (e.g. Han et al., 2017; Vassileva and Campillo, 2017), but few articles offer insight into the relationship between OEMs and governments.

In other words, in order to analyse EV innovation and the role of governments, one cannot rely on technological innovation theories without an up-to-date case study that covers the relationship between OEMs and governments. And indeed, there are many barriers to EV promotion, but governments need to prioritise with limited resources. Thus, we need to see the barriers from a structural perspective in order to find the relevance among the six barriers I mentioned in the previous chapter, and to judge which barrier governments should prioritise. Therefore, I will try to give a structural overview of the barriers to EV development through a technological innovation theory and contemporary examples. And then I will subsequently specify research questions covering the important factors that prevent EV promotion.

3.2 Structural overview of the problem of EV penetration

As the basis of the structural overview, I will use the 'multi-level perspective' analytical lens developed by Geels (2002), which I referred to above in 2.1.3. This is not only because Geels is a pioneer in this field (he is chairman of the international Sustainability Transitions Research Network), but also because it is suitable to depict the obstacles from a long and dynamic perspective. My purpose is to offer insight into how existing societies based on ICEVs and fossil fuels can transition to EV usage, and into the role of governments in this transition.

3.2.1 Geels' theory and framework for analysis

Geels (2002) contends the technological transitions as follows. An interplay between multi-dimensional developments at three analytical levels leads technological transitions. He explains the thee levels are niches (the locus of radical innovations), socio-technical regimes (the locus of established practices and associated rules that enable and constrain incumbent actors in relation to existing systems), and an exogenous socio-technical landscape. And he outlines his core logic as follows (Geels, 2014):

- Niche-innovations have internal momentum (through learning processes, price and performance improvements, and support from powerful groups).
- Changes at the landscape level create pressures on the socio-technical regime.
- Destabilization of the regime [meso level] creates windows of opportunity for the diffusion of niche-innovations.

He also gives figures which demonstrate technological transitions (Figure 3.1 and 3.2).

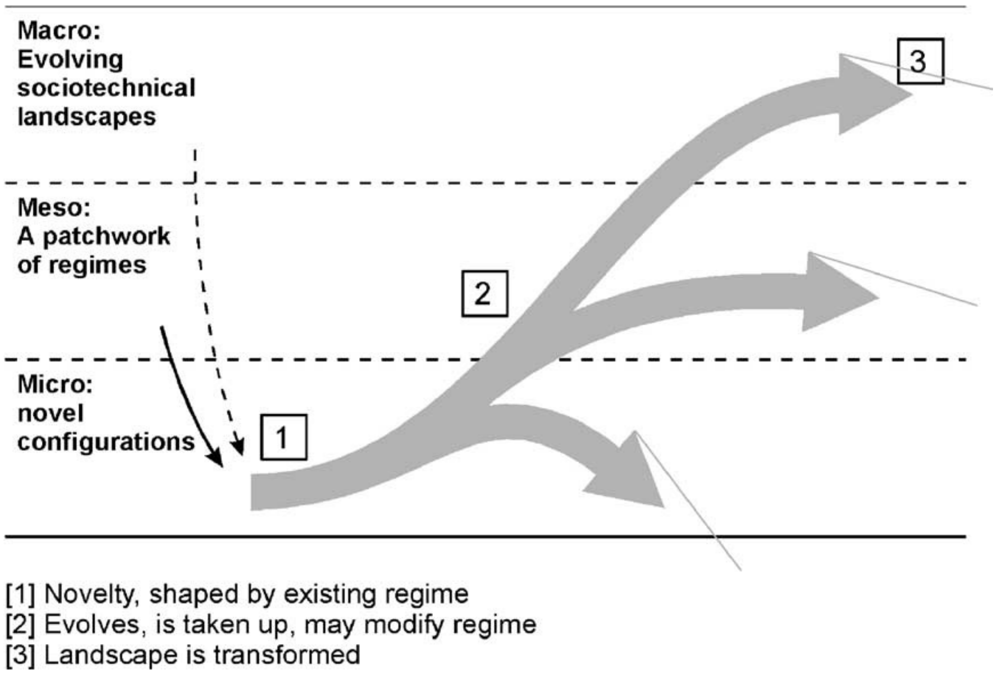

Figure 3.1 The dynamics of socio-technical change (Geels, 2002) [2]

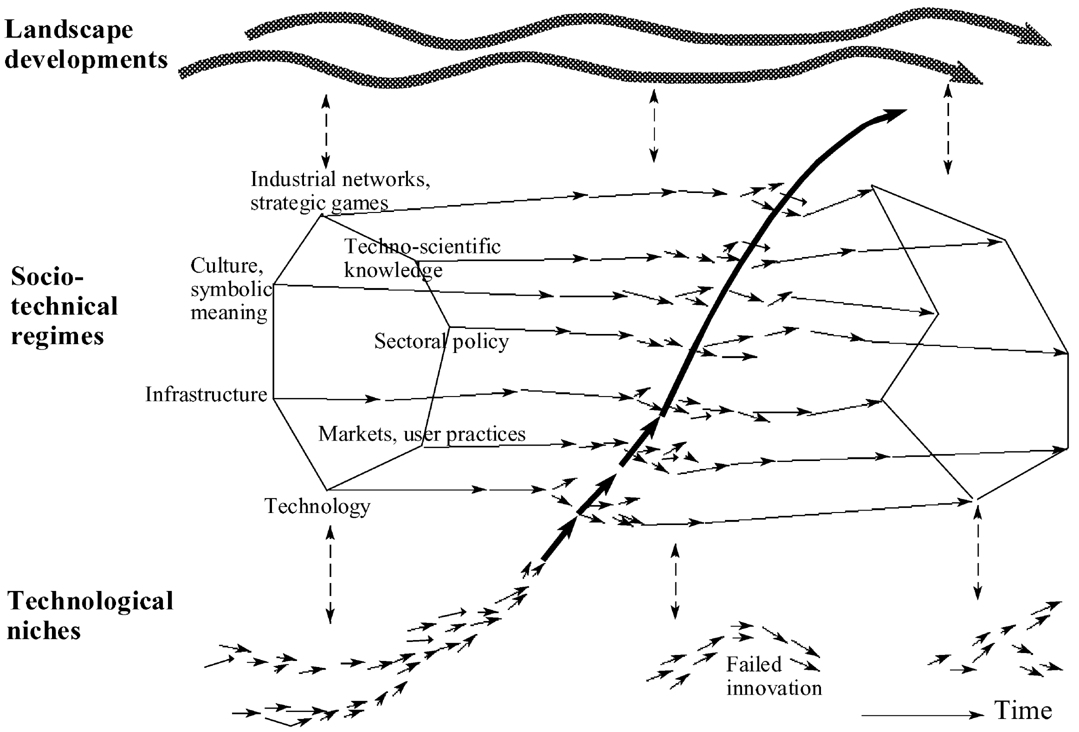

Figure 3.2 A dynamic multi-level perspective on Technological Transitions (Geels, 2002)

Figure 3.1 shows how technological transitions start in niches. The narrow arrows indicate that the emergence of the micro level (niches) is strongly influenced by the meso level (existing regimes) and macro level (landscape). Geels contends that whether the technological

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[2] Both Figure 3.1 and 3.2 are reprinted from Research Policy, 31 (2002), Geels, Technological transitions as evolutionary reconfiguration process: a multi-level perspective and a case-study, pp.1257-1274, with permission from Elsevier that is the publisher of the journal.

transitions have succeeded depend on not only the process within the niche level, but also the developments at the contemporary regime and the landscape level.

Figure 3.2 depicts how technological transitions change the landscape. The wide long arrows situated at the top show that changes to the landscape, such as cultural changes, demographic trends, and broad political changes, usually take place slowly. These changes may put pressure on the socio-technical regime, defined as ‘the semi-coherent set of rules carried by different social groups’, as well as the niche level demonstrated in Figure 3.1.

The three layers (technological niches, socio-technical regimes, and landscape developments) have internal dynamics but link to each other and co-evolve, so Geels uses shorter diverging arrows to indicate tensions and uncertainty among them.

To look at each level in depth: at the niche level, there are many small arrows going in different directions. Geels explains that there are various seeds of radical innovations that pursue each direction because a dominant design for future landscape has not yet established. After the dominant design is established, those radical innovations become gradually stable and converge with the dominant design. So, the arrows grow longer and fatter. In Figure 3.2, relatively long arrows mean the regular ongoing incremental processes.

As to the process of influence from niche to meso level, Geels contends that the process happens gradually as long as the radical innovations get used in subsequent application domains or market niches.

He also insists that the gradual change is also the case at the meso level. He defines the meso level as a ‘socio-technical regime’ consisting of various elements like markets, user groups and user practices, technologies, production networks, and policies. Geels claims that the introduction of new elements in the existing regime makes other elements change their incentive structures and situation, thus the process of shifting assemblies or reweaving and reconfiguration of socio-technical elements is happening through the technological transitions. He also introduces an important logic of, ‘cascade dynamics’, which means that changes in an element of the regime results in changes in other elements, in turn, these changes trigger further changes in the other elements. The dynamics leads to the reconfiguration processes of the socio-technical regime. That is, each component of a socio-technical regime has the potential to trigger a total shift in the regime.

As to the mechanism I mentioned in Figure 3.1 of stimulating the niche level at the regime level, Geels says that if the regime is confronted with problems and becomes destabilization, the connection among the regime gets loosen up, and this makes opportunities for radical innovations to develop from niche-level and to be a part of the socio-technical regime. Therefore, in Figure 3.2, a two-headed arrow between two levels appears.

In summary, technological transitions are realised not only by changes in technology and market shares but also changes on broader socio-technical axes such as regulation, infrastructure, symbolic meaning, industrial networks. These changes are triggered in turn when some component of the regime changes. The process of the shift of a socio-technical regime is represented by the increased density of arrows at the centre of Figure 3.2.

Once the new regime is established, it changes on the landscape level, and fulfils the technological transition. On the right side of Figure 3.2, you can see that the heptagon has changed to a new one and relates to the new landscape.

Geels concludes that the breakthroughs of innovations depend on the processes of the level of regimes and landscapes those are context-dependent, and that the reconfiguration in the regime level is step-by-step process, thus technological transitions do not occur suddenly, and we need to the multi-level perspective for analysing the transitions.

In other words:

- Technological transition does not happen only on the niche level (technologies), so it is necessary to also shift the macro (landscape) and meso (socio-technical regime) levels.
- In order to shift the meso level, we need reconfiguration of each component that consists of socio-technical regime today, and the reconfiguration will be triggered by the change of a component.

3.2.2 Adaptation of Geels' theory and framework to the EV case

I will put the six barriers of EV promotion I have raised in the previous chapter into the Geels' framework in order to find the relationship among them, and specify my research questions. First, I will make clear what the three levels in the framework mean in the case of EV, and put the barriers with analysing up-to-date situation, and predict the expected governmental role.

1) Niches (technological radical innovation)

Barrier 5 (insufficient performance of EV) fits this level. As a potential consumer, one can easily list some obstacles to purchasing EVs. The purchase is much more expensive than that of an ICEV, there is additional inconvenience for charging, and the consumer is anxious about the short cruising range. The average EV today drives around 300km on a full charge (Table 3.1). In addition to the short average cruising range, because the driving ranges that are announced by OEMs are measured in closed laboratories (in which drivers do not use air conditioners) by driving on a chassis dynamo (receiving less resistance than from a real road), the real driving range is shorter than what is advertised. These problems are the consequences of the technological problem of a battery and charging system. It is also said that the battery is the major reason for EVs' costliness, as I will mention below. The dilemma is that in order to extend cruising range, one would need to load many batteries into the EV, but this would make the EV more expensive, and it would also require a longer charging time.

Table 3.1 Driving range of representative EVs (measured by NEDC mode) (source: official catalogue of each OEMs)

OEM	Brand	Driving range
Nissan	LEAF	378km
VW	E-up!	160km
	E-Golf	300km
BMW	i3	300km
Tesla	Model S	490km

The potential solutions to these problems stem from technological development. Currently, we use lithium ion batteries for EVs, but in the future, we may use new types of batteries (e.g. solid-state battery, lithium sulphur battery, air material battery) which are expected to reduce battery cost and extend cruising distance. Moreover, contrary to the case of ICEVs which can be refuelled in just minutes at a gas station, a thirty-minute wait is required even when using a high-speed charger for an EV today, but in the future, they may be charged on the street automatically with wireless charging technology (Li and Mi, 2015). As Geels says, these technological developments will provide internal momentum for the shift towards EVs. Therefore, it is important to stimulate research and development around these kinds of technologies through governmental support.

2) Socio-technical regimes

Barriers 1, 2, 4, and 6 belong on this level. I will discuss them one by one as follows.

As to barrier 1, the low production volume and productivity of EVs is regarded as immature ‘market’ and a ‘culture’ unsuited to EV usage, at Figure 3.2. Conversely, the EV transition have potential to create another market and new culture. That is, the transition will stimulate other economic activities like energy management services using batteries in EVs, self-driving systems, and vehicle-sharing related to a distributed charging system. To be more specific, the batteries in EVs can absorb excess utility generated by renewable energy whose generation is difficult to adjust; some companies try to develop business models which aggregate the battery capacity of EVs, the time spent charging them, and the generation of renewable energy, with the use of IoT (internet of things) technologies. EVs also work well with self-driving technology because EV motors can respond more rapidly and easily than internal combustion engines. EVs also synergise with car-sharing services because the user can easily collect and drop off EVs due to the many charging spots (if we utilise existing electricity infrastructure).

That is, EVs have sufficient potential for ‘opening a vast innovation opportunity space’ as Perez said (Perez, 2010) and increasing the effectiveness of many industries and activities, but, current situation of low production volume and productivity prevent them. And it is equal to say that if the barrier gets loosen, many windows get to open to Niche levels, and many minor innovations follow.

As to barrier 2, the technological network centred on ICEVs and fossil fuels corresponds to ‘industrial networks’ and ‘sectoral policy’ in Figure 3.2.

For OEMs, the struggle to combine many components of ICEVs efficiently is a site of competition (Prahalad and Hamel, 2000). This is not only true of engineering, but also manufacturing. To be specific, ever since Ford manufactured the Model T in 1908, OEMs have striven to optimise the production of different components with low costs and high speed. Thus, it is said that the shift from ICEVs to EVs will mean a profit reduction for OEMs because the revenue from ICEVs that can be engineered and manufactured efficiently will decrease, and the revenue from EVs that have not been produced efficiently will increase, as long as the shift (Steinhilber et al.,2013). For example, Morgan Stanley suggests that if VW increases its EV sales portfolio to 4% by 2025, and 10% by 2030, this being a fairly conservative estimate (as can be seen in Table 3.2), this would decrease the company’s earnings before interest and taxes (EBIT) from 1.5 billion euros to a negative amount by 2025, and it would continue decreasing until 2027, when EVs’ profitability would improve (Forbes, 2016, online). And it is said that many newcomers will manufacture EVs because the necessary components are more easily assembled than those of ICEVs, so the barrier to entry seems to be lower. In fact, some reports indicate that companies such as Dyson may enter the EV market (Financial Times, 2018, online).

The fear of losing competitiveness and profitability is also relevant to ICEV suppliers. As I mentioned in the introduction chapter, the many suppliers and workers around ICEVs form a technological network. In addition to the technological network, regarded as the internal dependency, ICEV also has an external dependency. That is, it relates to industries such as filling stations, repair shops, recycling, and so on. These factors increase fears about job destruction through the transition to EVs from ICEVs, and represent a strong opposition to the penetration of EV. For example, the Petroleum Association of Japan, an organisation with strong political power, is against EV promotion, and even claims the tax imposition on EVs which makes equal footprint to ICEVs. The association contends that the users of ICEVs pay tax on fuel and this tax is used to construct and maintain roads, however, the users of EVs do not pay the tax for the purpose (Petroleum Association of Japan, 2017, online). And a decrease of oil demand means a decrease in tax revenue from ICEVs.

Thus, there are inertia derived from technological network in the ICEVs and fossil fuels based society (Steinhilber et al.,2013). This is also the case in Germany, which has many automobile-related industries. In October 2016, Germany permanently adopted a statement aiming to prohibit sales of ICEVs after 2030, but a governmental spokesperson warned against banning the sale of ICEVs in July 2017 (Reuters, 2017, online), and prime minister Merkel announced in September that they are needing combustion engines for decades. She went on to say, ‘combustion engines plus electromobility, that's how we can avoid driving bans being imposed on diesel vehicles’ at a Frankfurt auto show (The Federal Chancellor of Germany, 2017, online). The German government, then, is cautious of abandoning ICEVs.

The Japanese government has also taken the careful stance of only accelerating EVs. The Minister of Economy, Trade, and Industry said during an interview that EV had some problems to overcome, such as securement of battery resources and long time for charging, thus in order to react to the situation of uncertainty surrounding the automobile industry, it was important not to depend on one technology, and to develop not only EV but also FCV (METI journal, 2018). It is notable that both governments made agreements to incorporate many fields including policies for the automobile industry in May 2017, and 'basic research on internal combustion engines' was included alongside other projects like standardisation of charging (METI 2017, BMWi, 2017). It seems that countries whose competitiveness relies on their automobile industries want to keep improving internal combustion technologies, and are not willing to exclude ICEVs from society at once.

Of course, new industries will arise with the expansion of the EVs. The battery industry is expected to grow dramatically. The EU initiated a 'European battery alliance' consisting of mining companies, OEMs, and chemical industries in October 2017 (EU, 2017b, online). This movement seems to stem from fear of job destruction, because 90% of global battery manufacturing depends on China, Japan, and South Korea today (Politico, 2018, online). The EU officially announced: 'Currently, the EU has no capability to develop and mass produce battery cells – the most expensive item of an electric car', and explained the aim of the European battery alliance as 'to prevent a technological dependence on our competitors and capitalise on the job, growth and investment potential of batteries, Europe has to move fast in the global race' (EU, 2017b, online).

Thus, the countries and regions which profit from ICEVs do little to encourage the shift to EVs or disincentivise ICEVs due to the strong ICEV-based technological network, and anxiety about job destruction or a loss of competitiveness which could accompany the shift (Economist, 2018, online).

As to barrier 4, the further construction of charging stations is an issue of 'infrastructure', and as to barrier 6, the business strategies of OEMs corresponds to 'strategic game' in Figure 3.2. To more specific about the barrier 6, contrary to ICEVs, consumers cannot compare EVs among OEMs well because few OEMs offer them, and this limited option of EVs has played the role of barrier to the enlargement of the EV market. For example, consumers who want to buy SUV (sports utility vehicle) can find only few models of EV in their market (only Tesla model X they can find in developed countries up to now), so they cannot judge the EV is affordable price and performance compared to others. This finding is also verified by the interview, I will present in the next chapter, from the leading EV company Nissan. The interviewee says the lack of EV competitor has led to immature EVs market.

It is true that many OEMs have announced aggressive goals for 'electrification' in this several years, but not for EVs. As can be seen in Figure 3.3, 'electrification' is a broader concept than EV because it includes not only EV but also hybrid vehicles (HV), plug-in hybrid vehicles (PHEV), and fuel-cell vehicles (FCEV). HVs are powered by two energy sources, motors and engines, and there are many types of HV differentiated by what proportion of the power is supplied by the motor. Both vehicles whose motors only assist the engine with acceleration (mild HV) and those whose motor works when the vehicle drives at a low speed (strong HV) are included under HV in the definition of 'electrification'. That is, electrified cars include both HVs and PHEVs, which have internal combustion engines, along with EVs and FCEVs, which can be driven exclusively by motors, meaning that they do not discharge CO2 while driving. It is noteworthy that companies pushing aggressively for electrification will not only sell EVs, as I show in Table 3.2. Only VW set a target specifically for EVs.

Volvo cars announced their goal of fully electrification after 2019, and the CEO of Volvo cars in Japan explained the meaning of the announcement at media interview. He explains that the main portfolio of electrified will consist of mild HVs, which is mainly driven by the internal combustion engine, and PHEVs. He also says that the strategy does not mean Volvo cars will shift to EVs dramatically and rapidly, and it seems that the strategy is mistakenly understood a bit by media. He predicts that for the time being, Volvo cars will sell mild HVs mainly, and it will be 80% of total sales' (Diamond, 2017, online).

Thus, indeed many OEMs have announced the goal of electrification, further development of business strategies for the promoting EVs is needed in order to diffuse EVs into markets.

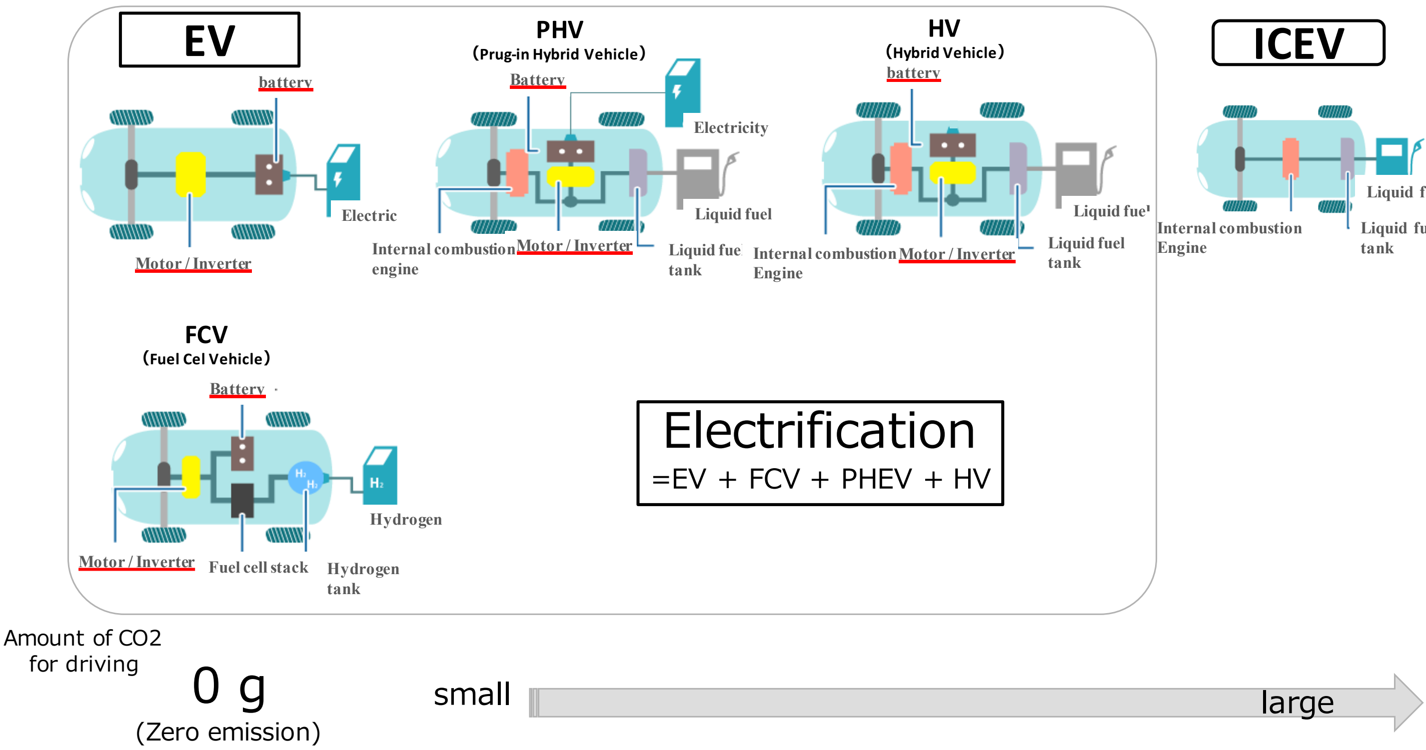

Figure 3.3 The difference between 'electrification' and EVs (Modified from METI, 2018, online)

Table 3.2 Goals of "electrification" for OEMs (Source: Official Webpage of each OEM)

	Toyota	Nissan	Volvo	VW
Date and Title	December 2017 "Toyota Aims for Sales of More Than 5.5 Million Electrified Vehicles Including 1 Million Zero-Emission Vehicles per Year by 2030"	March 2018 "Nissan aims to sell 1 million electrified vehicles a year by FY2022"	June 2017 "Volvo Cars to go all electric"	June 2016 "TOGETHER – Strategy 2025"
Sales volume	**By around 2030,** Toyota aims to have sales of more than 5.5 million electrified vehicles, **including more than 1 million zero-emission vehicles (BEVs, FCEVs**).	Nissan is aiming to sell **1 million electrified vehicles – either pure electric models or those with e-POWER powertrains** – annually by fiscal year **2022**	-	The Volkswagen Group forecasts that **its own BEV sales will be between two and three million units in 2025, equivalent to some 20 to 25 percent of the total unit sales** expected at that time
Market	Toyota will accelerate the popularization of BEVs with **more than 10 BEV models** to be available worldwide by the early 2020s, **starting in China**, before entering other markets—the gradual introduction to Japan, India, United States and Europe is expected.	-Develop **eight new pure electric vehicles**, building on the success of the new Nissan LEAF -Launch an electric car **offensive in China** under different brands -Introduce an electric "kei" mini-vehicle in Japan	Volvo Cars will introduce a portfolio of electrified cars across its model range, **embracing fully electric cars, plug in hybrid cars and mild hybrid cars**. It will launch **five fully electric cars between 2019 and 2021**, three of which will be Volvo models and two of which will be high performance electrified cars from Polestar, Volvo Cars' performance car arm. These five cars will be supplemented by a range of petrol and diesel plug in hybrid and mild hybrid 48 volt options on all models, representing one of the broadest electrified car offerings of any car maker. This means that there will in future be no Volvo cars without an electric motor, as pure ICE cars are gradually phased out and replaced by ICE cars that are enhanced with electrified options.	The Volkswagen Group is affirming its expansion and investment plans already announced for **North America** and its continued expansion program in **China**.

** "e-POWER" of Nissan is HV*

As I analyse above, there are many barriers at the socio-technical regime. These components of the regime level collectively constitute the barrier to introducing new technologies as a whole. For example, the business strategy of OEM (Barrier 6) decides the production volume and productivity of EVs (Barrier 1), while the technological network of ICEVs (Barrier 2) affects business strategy (Barrier 6). In other words, if this regime becomes destabilised, many doors will open to new technological innovation (niches). That is why 'destabilization' is keywords.

3) Landscape level

Of the six barriers I mentioned in the previous chapter, none correspond to the landscape level. This level can create pressure at the regime level by forcing a decrease in carbon emissions, so more pressure may be needed for technological transition, but there have already been many movements to promote EVs at a global level as I mention below.

On September 2015, the UN (United Nations) adopted 'sustainable development goals' intended to protect the planet as well as to end poverty and ensure prosperity for all (UN, 2015). There are 17 goals, including zero hunger, gender equality, clean water and sanitation, etc., and each goal has specific targets to be achieved over the next 15 years. 'Climate action' and ‘sustainable cities and communities’ are also set as goals. Furthermore, in order to address ‘climate action’, almost all countries adopted the Paris Agreement in December 2015, agreeing to work to limit the global temperature rise to well below 2 degrees Celsius. Since exhaust emissions from ICEVs contribute to global warming and air pollution, the improvement of automotive technology, including EVs, can play a crucial role in overcoming these global challenges.

At the international level, other than the UN, IEA launched a multi-government forum named ‘The Electric Vehicles Initiative’ (EVI) to promote EVs in 2010. It was initiated by the Clean Energy Ministerial (CEM), a high-level dialogue among energy ministers from the world’s major economies, and the members of EVI are Canada, China, Finland, France, Germany, India, Japan, Mexico, the Netherlands, Norway, Sweden, the United Kingdom, and the United States. In 2017, CEM announced the ‘EV 30@30’ campaign, which aims to accelerate EV promotion and target at least 30% new electric vehicle sales by 2030 (IEA, 2017b, online). Compared to today’s level, 1%, the 30% target is highly ambitious.

Many governments, including those of developing countries, are trying to shift from ICEVs to EVs, influenced by the international movement and initiative. For example, in 2017, the UK’s government agency for environmental affairs announced the prohibition of gasoline and diesel vehicle sales after 2040, while France announced a similar prohibition on vehicles which emit greenhouse gases (The government of UK, 2017; French government, 2017). Indeed, both announcements neither mentioned how to deal with HVs or PHEVs, they impress us the EV shift has started. The Japanese government also announced to aim at increasing the market share of Next Generation Vehicles (consisting of EV, FCV, PHEV, HV, etc.) among new car sales to between 50% and 70% by 2030 (METI, 2014). The German government also has the aim to have one million electric vehicles on Germany’s roads by 2020 (BMWi, 2014).

Thus, it is obvious that there are few obstacles and barriers at the landscape level, because EV promotion is a major agenda authorised by UN, international forum, and many governments, and being pursued officially.

3.3 Aim and research questions

Through the adaptation of Geels’ theory and framework to the case of EV, problems are discovered to exist on the niche (technological revolution) and meso levels (destabilisation of socio-technical regime). Support for technological development and the destabilization of socio-technical regime are expected to be the governmental role. However, technological revolution is insufficient to fulfil technological transition, and there is huge uncertainty in the technological progress. Thus, I will analyse the shift on the meso level not only because I found many barriers there, but also because Geels (2014) has suggested we need further research on destabilisation on this level in order to set effective policy.

The socio-technical regime consists of many components, including markets, user groups and practices, technologies, production networks, and policies. I will focus on the relationship between business strategy (Barrier 6) and policies, and set research questions. The reasons are as follows:

- Business strategy relates to production volume and productivity (Barrier 1), and also affects the performance of EVs through R&D activity (Barrier 5).
- Indeed, charging infrastructure (Barrier 4) is important for EV promotion, and governments should play a supporting role. The relationship between EVs and infrastructure is 'chicken and egg', so both further construction of charging infrastructure and aggressive EV-focused business strategies are needed to diffuse EVs.
- There is a suggestion that policymakers should focus on how to let OEMs improve their offer of EVs (Kieckhäfer et al, 2017), but there are few studies that focus on the relationship between OEMs and governments.

To be specific, I will explore following research questions with the latest data, in an attempt to deepen the academic discussion of innovation policy with this case study:

A) How can OEMs shift their business strategies (sales portfolios) from ICEVs to EVs?

B) What is the role of government and innovation policy in promoting this shift?

I conjecture that this thesis will suggest that effective innovation policy involves not just supporting consumers purchasing EVs and companies performing R&D activity, but legislating aggressive regulations for OEMs in order to incentivise and promote the development of EVs. As Wesseling et al. (2015) point out, the EV market penetration depends on the strategy of OEMs, which is based on their assets and incentives for promoting EVs. Regulations can play the role of both putting pressure on OEMs and increasing their incentive to participate in the EV shift. Through regulations, a shift in OEMs' strategies, and competition among OEMs, the socio-technological regime will start to fully shift and consumers will be able to gain high functional values from EVs, causing the market to grow. This will result in the evolutionary reconfiguration of socio-technical regimes and the promotion of a technological transition. In fact, there are similar successful examples of governmental regulation leading to technological innovation in the automobile industry, such as the Muskie Act in the US from 1970, which imposed severe emission gas (NOx, CO and HC) regulation on OEMs, and resulted in competition among OEMs leading to the development of new technologies for reducing emission gas which have since been widely diffused (Gerard and Lave, 2005).

That is, the policy of setting aggressive regulations which incentivise EV promotion will have a domino effect. This change of components (policy) of socio-technical regime will trigger the change and destabilisation of the regime, rectify the malfunction related to evolutionary reconfiguration processes with multi-level perspective, and finally realise the technological transition from an ICEV- and fossil fuel-based landscape to an EV-based landscape. That is projection for the outcome of the research questions, and I will verify it as follows.

3.4 Methodology

EV-related technological innovation of EV is complex phenomenon, and there is no dominant theory to explain the current situation, so I adopt the qualitative method to explore research questions (Creswell, 2017). Moreover, I will focus on the case of developed countries because EV market penetration proceeds more quickly in developed countries than in developing countries. I will focus especially on Japan, Sweden, and Germany, because each country has competitive OEMs and an automobile industry, and the industries create many ICEV-related jobs. That is, these countries have the ability to create new technology and promote innovation, but they are also in strong 'carbon lock-in' and have a strongly ICEV-based socio-technical regime, so these countries are well-matched to the situation I previously examined structurally. Thus, the effective innovation policy in these counties has general applicability to EV promotion in other developed countries. I will verify the possible outcomes by combining two elements as follows:

1) Time series data related to OEMs' EV assets

Wesseling et al. (2015) show that the progressive attitude of OEMs to EV depends on both incentive and opportunity (equal to assets). In order to research how regulations have affected the changing EV assets of OEMs, I will analyse the relationship between the change of the asset and announcements or publication of regulations. I will collect some assets data with reference to the typology from Wesseling et al. (2015) that regards assets as 'patents related to EV and battery (as the core component)', and 'the number of EV prototypes at a prestigious international auto show'. I will set the data period from 2009 to 2017 because I want to minimise the effect of the economic cycle, especially the 2008 economic crisis.

I expect that the data will show assets increasing year after year, and also show the inflection year when the assets dramatically increased. I will analyse the relationship between the inflection year and the date of launch or announcement of governmental regulations that may have affected OEMs' EV strategies. I collect this data from the following sources:

- *Patents: Database of EPO (European Patent Office).*
- *EV prototype: website of Tokyo International Motor Show and website referring to Frankfurt Auto Show.*

I will collect data from Toyota, Volvo, and VW, the biggest OEM in each country to announce aggressive attitudes to electrification after 2016. I also collect from Nissan, which started to sell EVs in the global market in 2010 as 'leading OEM' in order to compare the effects on business strategy of regulations between Toyota, Volvo cars, and VW as 'following OEMs'.

2) Interviews with governments and OEMs

In order to explore the research questions in the context of the current situation, I conducted interviews with both governments and representative OEMs in each country as much as possible. The purpose of the interviews was to find what the subjects thought about the present situation and barriers to EV promotion, and how governments can affect their business strategies. I also inquired about what they thought of the results of the time series data related to OEMs' EV assets.

I managed to make interview to as follows.

- *Toyota: Director of technological affairs*
- *Nissan: Director of public relations*
- *Japanese government: Deputy Director of the automobile division at METI (Ministry of Economy, Trade, and Industry)*

The interviewee in the two OEMs, they have been representatives to negotiate with many governments more than five years, so they can make the comment in behalf of their companies. And the interviewee in the Japanese government, he has been the person in charge of planning governmental measure and target for promoting EVs for a year, so it is valid to ask the stance of the government about EVs.

I also tried to make interview to Volvo cars, VW, Swedish government (Ministry of Enterprise and Innovation), and German government (BMWi), but I cannot get any resopnse. Arguments about innovation policy and the business strategies around EVs are under discussion now, so the academic interview may be restricted from investigating the situation too closely because of confidentiality. However, I have succeeded in interviewing at both the leading and following companies (Nissan and Toyota), and at the Japanese government which is in communication with OEMs and other governments, thus the result of interviews seems to have general applicability.

The interview was conducted with open-ended question (see Appendix). And the interview data was transcribed and checked by the interviewee. For reasons of confidentiality, interviewees are anonymous.

4 Analysis and discussion

4.1 The current state of governmental regulation and OEMs' EV assets

Before I show the results of the time series asset data, I will specify the regulations that have affected OEMs' EV strategies in order to analyse the data in depth. In other words, I will find a turning point for OEMs' strategies by reviewing the current state of regulations.

It is insufficient to analyse regulations only in Japan, Sweden, and Germany in order to research the regulatory impact on OEMs' strategies. This is because OEMs sell their products to global markets, so R&D activity and sales promotions aim to address global markets, especially the major markets for OEMs, and not just those of the mother country. For example, as Table 4.1 shows, the US is the largest market for Toyota (the share of US market for global sales of Toyota is 25.4%), and China for VW (47.5%), and the sales share of US and Chinese markets for the OEMs (Toyota, Nissan, Volvo cars, and VW) is about 30 to 50%. Thus, the trend of regulations in these mega-markets affects OEMs' strategies (this is verified by the OEM interviews, as I will explore in the following section). I will review the trend of regulations in the US and China firstly, and review the trend in each mother country market (Japan, Sweden, and Germany).

Table 4.1 Major markets for OEMs (Source: Database of Marklines)

	Toyota	Nissan	Volvo	VW
1st market	**US** **25.4%** 2,129,178	**US** **28.8%** 1,440,049	**China** **17.0%** 91,052	**China** **47.5%** 3,135,236
2nd market	Japan 18.9% 1,587,062	**China** **22.3%** 1,116,709	**US** **15.2%** 81,504	Germany 10.4% 687,589
3rd market	**China** **13.5%** 1,131,618	Japan 11.8% 591,000	Sweden 14.1% 75,506	**US** **5.2%** 339,676
4th market	Indonesia 4.4% 369,733	Mexico 7.3% 364,557	UK 8.6% 46,139	Brazil 4.4% 287,301
5th market	Thailand 2.9% 239,551	UK 3.3% 167,003	Germany 7.6% 40,790	UK 3.8% 250,064
Sales share of US and China for OEMs	**38.9%**	**51.1%**	**32.2%**	**50.7%**

**Upper: Market name, Middle: Market share for total sales of the OEM, Lower: The number of car sales of the OEM*

4.1.1 Regulation trends in the US and China

In the past half-decade, influential regulation has started or been announced in the US and China. Automotive sales in these countries were 17,654,938 and 28,878,904 respectively in 2017, and the total global share of the two markets is about 50.3% (Marklins). Thus, OEMs' strategy depends on these two large markets.

In January 2012, California Air Resources Board (CARB) formally adopted the regulation plan that opposed big OEMs to sales requirements for EVs (or FCVs) at over 16% of new vehicle sales by 2025 (ZEV regulation)[3]. California is the biggest state in the US and has major influence on other states' policy. In fact, ten other states have adopted the same policy and the market share under the regulation is about 40% of the total US market. And in September 2016, China also published a draft of a regulation policy quite similar to ZEV (NEV regulation). In June 2017, the regulation was formally implemented and will come into effect in 2019.

These two regulations have had a crucial impact on the shift of OEMs' attitudes to EVs. This is because these ZEV and NEV regulations directly require OEM to produce EVs[4]. That is, other regulations like fuel consumption regulations (in Japan) and CO2 emission regulations (in Sweden and Germany) do not force OEMs to manufacture enough of a specific type of vehicle to pass the threshold of the regulation. Thus, OEMs are able to select the type of vehicles they manufacture, like diesel car, hybrid vehicle, in addition to EV, depending on their assets and strategies, as long as they pass the regulation. Contrary to the conventional regulations, the new type of regulations restricts OEMs' strategies in terms of what kind of technologies they adapt.

4.1.2 Regulation trends in Japan, Sweden, and Germany

The Japanese government has regulated fuel consumption, and in 2012, the government published a target for OEMs in the Japanese market to clear after 2020. Each the OEMs is required to clear an average fuel consumption, that differs between the companies depending on their sales portfolio (average level of all OEMs is 20.3L/km). This is called 'CAFE: Corporate Average Fuel Economy', and the OEMs can arrange their sales portfolio depending on their technological strength. However, since 2014, the average fuel consumption of all OEMs has already satisfied the standard that was expected to be cleared after 2020. In 2014, annual EV sales in the Japanese market were only 0.34% (METI, 2015, online), so it can be concluded that the regulation did not effectively incentivise the OEMs to promote EVs. It

[3] Strictly speaking, the OEMs should get credits equivalent to the 16%. Depending on the driving range, the credit that the zero emission vehicles get differ. This is also the same to NEV regulation.

[4] Indeed, the OEMs can select FCV, but the technological development of FCV is slower than that of EV. And PHEV is less advantage to EV at the regulations. Thus, the OEMs should react to the regulations by selling EVs.

seems that this is because the regulation is technologically neutral, so OEMs do not need to develop EVs in order to comply with the regulation.

Sweden and Germany both fall under the EU's CO2 regulations, CAFE, and OEMs in these markets are supposed to satisfy the average CO2 emission target of 95g/km by 2020. The target was announced at 2012. It is said that the EU regulation provides more incentive for EVs than the Japanese regulation, because the EU regulation regards EVs as zero-emission and does not take into account amount of CO2 for generation. The fuel consumption regulation in Japan is measured by 'L/km', so it is necessary to convert electricity consumption per kilometre to fuel consumption per kilometre with the formula of energy translation from electricity to oil. This means that in the case of the Japanese regulation, EVs are regarded as using oil (equal to saying they emit CO2). Thus, the regulation in EU provides more incentive for EVs than the Japanese one, however, in contrast to ZEV and NEV regulations, even the EU regulation is as technologically neutral as the Japanese one, so the OEMs are not required directly to bring EVs to the market. Dijk and Yarime (2010) argue that the European regulations have played the role of incremental innovation around ICEV technologies, but they have not caused radical innovations around electrification and escape from lock-in (Dijk and Yarime, 2010).

As I will mention in the interview section, the interviewees explained that since 'dieselgate' in 2015 (the scandal over the fact that VW's diesel vehicles were found to emit much more exhaust gas than regulation allowed), the sales of diesel, previously regarded as eco-friendly, have been decreasing, and OEMs in the European market must promote 'electrification' in order to satisfy the CO2 regulation without diesel. In other words, between the announcement of CO2 regulation in 2012 and dieselgate in 2015, the regulations had not played important a role to push OEMs to electrification, and needless to say EVs.

To summarise, it seems that as turning points, the years around 2012 and 2016 were epoch-making in terms of OEMs reconsidering their business strategies, and regulations like the ZEV and NEV regulation in the US and China motivated OEMs to develop EVs more than the equivalent regulations in Japan and Europe. In order to verify how these epoch-making events have affected OEMs' strategies, I have collected various data which are further discussed in the following section.

4.2 Patent data

Firstly, I collected data related to OEMs' EV assets during the period from January 2009 to December 2017. Since patents are the traditional determinant for measuring technological assets, and the battery is the key component of an EV, thus as the way of Wesseling et al (2015), I collected the patent data of OEMs including the terms 'electric vehicle' and 'battery' in the European Patent Office's (EPO) Patent Database. The database contains patent publication data as well as the name of the applicant and abstract information about the patent. The database covers patents that applied to Europe, US, Japan, and China, and OEMs tend to apply patents not only to their home country but also to countries with major markets, so this database makes it plausible to follow the technological trend of OEMs. However, even if there are more than 500 results in the database, the website only shows the total number of results and does not show the detail of all the patents, and the results in relation to Toyota and Nissan were over 500 when I searched with the same conditions as I did for Volvo cars and VW, so I needed to change search terms depending on the OEMs' situation in relation to EVs.

I recollect the patent data with the term 'solid-state battery', one of the potential future batteries for EV, as the asset of Toyota. There are two reasons why 'solid-state battery' is relevant. First, the solid-state battery is regarded as one of the next generation batteries for EVs after the lithium ion battery today. Compared to the lithium ion battery, the solid-state battery does not have liquid as a conductor, and uses a solid-state conductor instead. This solid conductor enables higher battery capacity, and increases safety because it has less risk of burning than the lithium ion battery.

Second, Toyota has officially announced that it is focusing exclusively on solid battery technology as the main battery for its future EVs. In December 2017, Toyota stated: 'Batteries are a core technology of electrified vehicles and generally present limitations relating to energy density, weight/packaging, and cost. Toyota has been actively developing next-generation solid-state batteries and aims to commercialize the technology by the early 2020s' (Toyota, 2017).

Nissan, unlike Toyota, has not announced officially what type of battery it aims to install in future EVs, so I searched the patent with term '"electric vehicle"' not hybrid electric vehicle' in order to limit the result number to under 500.

Since the progress of the development of EV has differed OEM to OEM as Table 4.2 (for example, Volvo cars has not sold any EV as far), and there is a limitation of the database that cannot show all information the case of more than 500 results, thus I use the search terms differ across different OEMs, but what I need to analyse is how EV assets in each company have changed, and the relationship between the turning points and the change, so the different search terms do not directly invalidate the results.

The result is Figure 4.1 and Table 4.2, in which I also put some examples of patent information, number of patents, and search terms of each OEM. The result shows that all companies have increased their patents almost consistently.

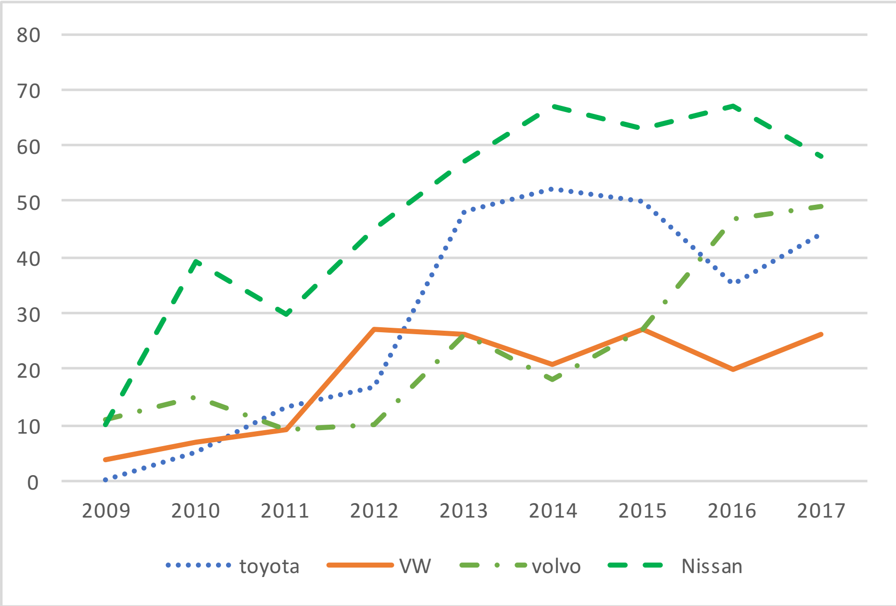

Figure 4.1 The time series data of patent (Source: EPO)

Table 4.2 Summary of the patent analysis

	Toyota	Nissan	Volvo cars	VW
Total EV sales until 2017 and shipment year	19 eQ (2012-)	289,950 LEAF (2010-)	-	7,151 e-up! (2013-)
Condition for patent search	solid-state-battery	"electric vehicle" not hybrid electric vehicle	"electric vehicle" and "battery"	"electric vehicle" and "battery"
Number of patents filed (After 2009)	264	440	212	167
Example of the patents	**<About System>** "MANUFACTURING METHOD FOR ALL-SOLID-STATE BATTERY,..." (2017) "SYSTEMS AND METHODS FOR BATTERY MICRO-SHORT ESTIMATION " (2015) "CHARGE CONTROL DEVICE FOR SULFIDE-BASED ALL-SOLID-STATE BATTERY"(2014) **<About Component>** "METHOD OF MANUFACTURING ELECTRODE FOR SOLID-STATE BATTERY" (2013) "METHOD FOR PRODUCING SOLID ELECTROLYTE MATERIAL-CONTAINING SHEET" (2012) "CATHODE ACTIVE MATERIAL, CATHODE ACTIVE MATERIAL LAYER, ALL SOLID STATE BATTERY AND PRODUCING METHOD FOR CATHODE ACTIVE MATERIAL " (2011)	**<Improvement of EV>** "VEHICLE-TO-GRID SYSTEM CONTROL BASED ON STATE OF HEALTH" (2015) "NONCONTACT POWER FEEDING APPARATUS AND NONCONTACT POWER FEEDING METHOD" (2013) "Display device for electric vehicle" (2012) **<Before the first shipment of EV (December, 2010)>** " CONTROL DEVICE FOR ELECTRIC VEHICLE" (2010) "ESTIMATION METHOD FOR CHARGEABLE/DISCHARGEABLE POWER OF BATTERY" (2009) "HIGH-VOLTAGE BATTERY UNIT MOUNTING STRUCTURE FOR VEHICLE" (2009)	**<Technologies essential for EV>** "METHOD AND ARRANGEMENT FOR DETERMINING A VALUE OF THE STATE OF ENERGY OF A BATTERY IN A VEHICLE" (2017) A METHOD AND SYSTEM FOR BALANCING A BATTERY PACK" (2017) "ESTIMATION OF BATTERY PARAMETERS" (2016) "System and method for determining usage battery limits" (2016) **<Not only focus of EV>** "Arrangement and method for voltage protection of an electrical load in a motor vehicle" (2012) "METHOD AND ARRANGEMENT FOR DISCHARGING AN ENERGY STORAGE SYSTEM FOR ELECTRICAL ENERGY" (2010)	**<Technologies essential for EV>** "VEHICLE POSITIONING FOR WIRELESS CHARGING SYSTEMS" (2015) "Method and device for heating and charging electric vehicle at low temperature" (2013) **<Not only focus of EV>** "METHOD AND DEVICE FOR CHARGING A BATTERY OF AN ELECTRIC OR HYBRID VEHICLE BY MEANS OF A HIGH-POWER CURRENT SOURCE" (2013) "Battery cell, particularly film cell for lithium-ion batteries of hybrid or electric vehicle, comprises cooling or heating structure for cooling or heating of battery cell" (2012) "Device for cooling battery cells of e.g. traction battery of electric vehicle, has heat pipe utilized as evaporator or part of evaporator of cooling circuit and connected with cooling circuit and/or separable from cooling circuit " (2011)

Each number related to the following OEMs (Toyota, Volvo cars, and VW) increased in the periods 2011 to 2012 and 2016 to 2017. These increases seem to relate to the announcements of ZEV regulation (in January 2012) and NEV regulation (in September 2016). The increases at Toyota and Volvo especially accelerated since 2012, the year of the ZEV regulation's announcement.

On the other hand, in the case of the leading OEM, Nissan, the number of patent assets has increased consistently, and seems not to have been affected by the turning points.

Through analysing this patent data and comments from OEMs, I am convinced that the data is a good representation of trends related to EV assets at OEMs. And unlike at the leading OEM (Nissan), the increased number of EV assets at the following OEMs (Toyota, Volvo cars, and VW) has been affected by the regulations.

4.3 The number of EV prototypes at international auto shows

I also investigate the historical number of EV prototypes at international auto shows as an indicator of EV assets. At auto shows, a line-up of future products appears, so they are useful for predicting OEM strategies. As the way of Wesseling et al. (2015), I search the ratio of EVs in the total line-up of each OEM at the international auto-show. Toyota has sold an FCV (named 'MILAI') as a zero-emission vehicle, as well as EVs, and FCVs are treated the same as EVs under the ZEV and NEV regulations, I also counted the number of FCVs.

First, I collected time series exhibition data of Tokyo International Motor Show, which is held every two years and is one of the three biggest international auto shows (Japan is the third biggest automobile market in the world). This is because the website of the Tokyo International Motor Show displays the total prototype number of each OEM, so that from how many prototypes of EV they exhibited, I could calculate the EV ratio of the total exhibition. I searched what prototypes each OEM exhibited on each OEM's website. The result is below (Figure 4.2).

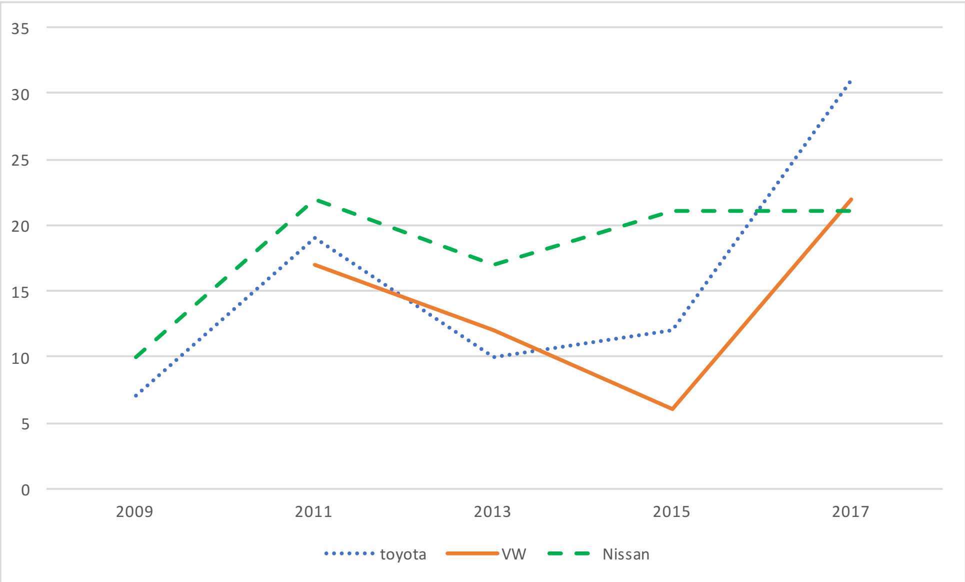

Figure 4.2 The EV ratio (%) of prototypes in each year's Tokyo International Motor Show

You can see that the following OEMs (Toyota and VW) increased their ratio dramatically after 2015. On the other hand, the leading OEM (Nissan) shows a constant high ratio since 2011. And Volvo cars have not exhibited any EVs.

I also collected data from the Frankfurt Auto Show, which is counted one of the biggest global auto shows. In contrast to Tokyo, Frankfurt's official catalogue and webpage does not show how many cars each OEM exhibited, so I tried to count numbers, not ratios, of EVs exhibited by OEMs from internet news and articles. I could not find any information that Toyota and Volvo cars have exhibited EVs or FCVs at the show. And Nissan didn't participate in the Frankfurt Auto Show in 2009 and 2017. Thus, only for VW was I able to collect historical data, displayed in Figure 4.3. Like the result from Tokyo, VW has dramatically increased its exhibition of EVs since 2015.

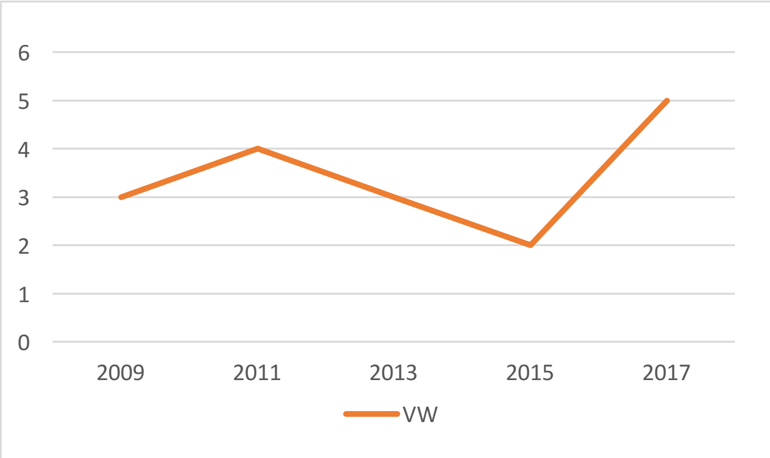

Figure 4.3 The number of EVs as prototypes in each year at the Frankfurt Auto Show

Incidentally, the interviewee at Toyota commented that the exhibitions at the auto shows included concept models that were not guaranteed to sell in the future, so unlike patent data, it was not suitable for finding the trend of EV assets for OEMs. Thus, it is better to consider this data from international auto shows complementary to the patent data. But, the data of both international auto shows indicates that the following OEMs (Toyota and VW) increased their ratio or number of EV exhibitions radically since 2015.

Through the data drawn from the patents and international auto shows, it appears that the announcement of regulations may have contributed to the increase of EV assets, especially in the following OEMs.

4.4 Interviews with OEMs and policymakers

In order to confirm my analysis, and the relationship between the OEMs' EV strategies and the trend of regulations, and to ask what they thought about the contemporary situation and obstacles to EV penetration and what they expect from governments, I tried to interview OEMs and policymakers in each country. I succeeded in interviewing at Toyota (following OEM), Nissan (leading OEM), and at the Japanese government.

4.4.1 Toyota

I interviewed the person in charge of technological affairs at Toyota in April 2018. As seen in Table 3.2, Toyota announced officially in December 2017 that ‘Toyota will accelerate the popularization of BEV [meaning EV] with more than 10 BEV models to be available worldwide by the early 2020s, starting in China, before entering other markets—the gradual introduction to Japan, India, United States and Europe is expected’ (Toyota, 2017). Although China is the third biggest market for Toyota (as evident from Table 4.1, it accounts for about 14% in 2017), and the US and Japanese markets are bigger than that of China (counting for approximately 25 and 19% respectively), Toyota have decided to sell EVs in China first. The interviewee said that the reason was the existence of the NEV regulation, which will come into effect in 2019 in China.

Toyota officially announced the sale of a prototype EV (named ‘eQ’) in September 2012 (Toyota, 2012), but the sales goal was only one hundred in the world. Only after five years, Toyota announced the new goal that aim to deliver ten EV models by the early 2020s, and sell one million EVs and FCVs in the world by around 2030 (Toyota, 2017). I asked what made Toyota launch their new aggressive EV strategy compared to the previous one, and the interviewee answered, ‘Many governments have announced and updated regulations during the period. And other OEMs have also published their strategies about electrification, so Toyota needs to announce new strategy’. These responses suggest that in this half-decade, the announcements of new regulations have accelerated competition among OEMs about strategies of electrification.

In the strategy, Toyota mentions that automobile demand is determined by ‘consumer’ and ‘market’. About the characteristics of each ‘market’, Toyota exemplifies the abundance of renewable energy (as in the case of Norway), and the scarcity of natural resources (as in the case of Japan), but I pointed out that regulation in each country was also one of the characteristic of the ‘market’. That is, Toyota react to demands and regulation is one of the elements Toyota regards as demand. The interviewee also said that ‘when we start to make concept of new vehicle, the tendency of regulations is the one of the top concern’, ‘research and development strategy is based on a forecast that regulations will be stringent, as well as the consumer preference and the strategies of competitors’, ‘you can tell that technological developments have promoted because of the existence of regulations’, and that ‘thus, appropriate regulations are motivation for us to propel research and development’. These remarks mean that regulations incentivise OEMs to promote EV development.

In summary, through this interview with Toyota, I can confirm that it is important to announce making regulations more stringent so that governments push OEMs to diffuse EVs into their markets through competition, and continue to research and develop new technologies. That the trend of regulation has affected the following OEMs in the last half-decade is evident from Toyota’s aggressive 2017 EV target.

I also asked the interviewee about the impact of electrification on job destruction. He answered, ‘For Toyota Motor company, the impact of the shift is a little. For example, the engineer who are specialist of catalyst engaged in R&D activity about the exhaust gas system in ICEV, but now, he engages in developing catalyst for FCV. However, many suppliers will be influenced by electrification’.

4.4.2 Nissan

I interviewed the person in charge of public relations at Nissan in May 2018.

In March 2018, Nissan published the goal of electrified vehicles to 2022, and then announced that they would 'launch an electric car offensive in China under different brands' (Nissan, 2018b). I asked the interviewee the reason why Nissan specified the target in China although China was only their second largest market. He replied, 'We are going to be obliged to sell EV at fixed ratio by NEV regulation' and 'There is big potential in Chinese market not only because the ratio of person who own car is still small, but also because EV is being regarded as ordinal car for Chinese consumer as long as EV market has expanded, and the huge Chinese market will play the role of testbed for further exploration to other countries'. Nissan is partly affected by NEV regulation, and has a vison to diffuse EV into the global market as the leading EV company.

Nissan has developed its future vison of EV. In 2011, in the previous mid-term plan, Nissan set the only global EV stock target by 2016 (Nissan, 2011). In March 2018, Nissan announced more detailed targets such as varieties of EV and EV sales forecasts in the biggest markets. I asked the reason behind this change and the interviewee replied, 'Nissan has adjusted its vison compared to other OEMs. In order to differentiate Nissan from other OEMs starting to announcement of EV target, it gets more important to announce target with concrete. In addition to the policy announcement these days by many governments of promoting electrification, dieselgate at 2015 has triggered such OEMs' announcement to shift electrification because the scandal made OEMs rely on electrified vehicles, instead of diesel'. From this remark and from the historical EV assets data of the following OEMs, I find that the regulations have increased EV assets for OEMs, and the scandal has triggered aggressive announcements from OEMs about electrification.

With regard to the nonattainment of the global sales goal set in 2011, the interviewee mentioned, 'The movement initiated by governments was not sufficient to diffuse EV' and 'Contrarily to the prediction, the function value of EV like driving range was judged insufficient by consumer. And secondary market of EV has not developed because of the low production volume of EV'. He also stated that the lack of EV competitors has resulted in an immature market and undeveloped secondary market. That is, potential consumers could not compare EVs among OEMs, so they also could not judge the value of an EV.

As to the regulations, he commented that 'without the regulations, the trend of electrification would not have come', but he also mentioned that 'Nissan is aggressive to promote EV in order to react global agenda as protecting environment, not to react the regulations. The regulations are one of the factor that encourage what Nissan wants to do'. That is, Nissan is not following the regulations, but utilising them to develop EVs.

And he said that 'we are not against policy measure of regulations. What is important is how to set good regulations that give OEMs motivation and incentive to develop EV. You should make balance between incentive and punishment. If punishment gets too severe, we need to supply unwelcomed EV for consumer'. Thus, Nissan wants government-set regulations that incentivise introducing EVs to markets, and that are not too stringent. He warned that if the regulations became too stringent, OEMs would have to produce EVs regardless of consumer preferences.

During the interview, I found that Nissan has developed EVs, and the regulations support the strategies. And it is an important insight that the leading OEM wants competitor in order to mature the EV market.

About the EV shift's impact on jobs and profits, he said that 'Nissan has decided to shift to EV, thus we just adjust our resources along with the shift'. He also mentioned the impact on suppliers: 'Both the cost for OEMs to suppliers and the number of suppliers will be increasing, for example OEMs will increase to order to chemical industries' and 'Indeed traditional suppliers about ICEV may feel worried, but the EV shift will need time (five to ten years) and ICEV will still be needed in the heavy-duty vehicles, therefore the supplies do not need to be pessimistic because they have enough time to shift their resources, depending of their strong point and knowhow'. As to the profitability of EVs, he said that 'it would be great if consumer bought EV willingly, without any effort of OEMs. But it is not true, thus, we need to make efforts like working economies of scales by increasing EV production volume, securing resources for battery, and developing alternative materials for battery to avoid risk of soaring material price (otherwise we will be suffered with huge deficit)'. From this remark, I confirmed that OEMs should take various actions in order to improve the profitability of EVs.

4.4.3 Japanese government

I also made interviewed a representative of the Japanese government (METI) in May 2018. I shared with the interviewee the idea that ZEV regulation and NEV regulation are the biggest factors in shifting OEMs' strategies to promote EV development. He also said, 'After the dieselgate scandal in 2015, European OEMs must have shifted their strategies from diesel to electrification in order to react not only the regulations in US and China, but also regulation in EU'.

As to the role of governments, he explained that 'in addition to support R&D activities, put incentive to consumer, and initiate infrastructure construction, we need to set new fuel consumption regulation that will encourage OEMs to develop EV. And how to shift business model of suppliers is also an important policy issue'.

Arguments about innovation policy and the business strategies around EVs are under discussion now, so the academic interview may be restricted from investigating the situation too closely because of confidentiality. However, I have succeeded in interviewing at both the leading and following companies, and at the Japanese government which is in communication with OEMs and other governments, thus the result of interviews seems to have general applicability.

4.5 Analysis of both data and interviews

Reflecting on the structural overview in the chapter three, and the data and interviews with the following OEM, leading OEM, and policy maker, I found that:

- Governmental initiatives (macro level) have made pressure to meso level to the EV shift, but they are not sufficient to promote a technological shift.
- The components of a socio-technical regime such as technology, user practices (e.g. expected performance like driving range), markets (including secondary markets), and business strategies (e.g. lack of competitors) have not been under reconfiguration for technological transition.
- Recently, EV assets have increased and the strategic game has heated up through the declaration of OEMs' strategies about electrification. Regulations have triggered this trend. In other words, at the level of socio-technical regime, the change of 'policy' has caused the change of 'strategic game'. And the competition through the change of strategic game, market maturing is expected. That is, policy shift (setting regulations that incentivise EV promotion) will have a domino effect for the evolutionary reconfiguration of socio-technical regimes, and the technological transitions.
- As to the technological network, it does not directly create barriers for OEMs, although the EV shift is a challenge for OEMs from the point of view of improving profitability. The barriers of technological networks are found more profoundly in suppliers rather than OEMs, as I interviewed from both the OEMs and the government.

As to the plausible outcome I mentioned in Chapter three that in order to fulfil the technological transition from an ICEV- and fossil fuel-based landscape to an EV-based landscape, the change of components of socio-technical regime (policy) is needed to trigger the change and destabilisation of the regime, restore the malfunction about evolutionary reconfiguration processes with multi-level perspective, I found that:

- So far, the new regulations in the large markets (US and China) have allowed OEMs (especially the following OEMs) to accumulate EV assets, and the dieselgate scandal in 2015 has accelerated this trend and the strategic business game among OEMs about electrification.
- Both leading and following OEMs desire adequate regulations in order to promote further development and shipment of EVs.

These findings will verify how aggressive regulations have played a central role in technological transitions by pushing OEMs' business strategies. Therefore, in order to proceed one step further from the electrification, and increase the ratio of EV stock in the Japanese, Swedish, and German markets, governments should set more stringent regulations which incentivise OEMs to promote EVs, and which trigger the change of components in the existing socio-technical regime, and fulfil the technological transition.

5 Conclusion

5.1 Research aims, objectives, and practical implications

Further EV diffusion is needed to meet global targets like preventing global warming and air pollution. Many governments have implemented supportive policies, but the speed of diffusion remains slow. Reflecting this situation, I have analysed the barriers to EV promotion and innovation by using the technological innovation theory suggested by Geels (2002). Today's ICEV- and fossil fuel-focused society ('landscape' in the theory) is associated with the stringent socio-technical regime that consists of OEMs' business strategy, technological network, infrastructure, policies, etc. The destabilisation of the regime plays a crucial role for technological transition, so in my thesis I have focused on the destabilisation and set the research questions as how can OEMs shift their sales portfolios from ICEVs to EVs, and what is the role of government and innovation policy in promoting this shift.

Moreover, based on the idea of Wesseling et al. (2015) that OEMs' EV strategies depend on their assets and incentives for promoting EVs, I have analysed time series data about patents and number or ratio of EV prototypes at international auto shows. Comparing the data with the years when influential regulations were announced in large markets (the US and China), I have found that the regulations can affect OEMs' strategy of accelerating EV development. Next to the data, I have also interviewed some OEMs and a government official, and I have verified that the regulations have encouraged OEMs (especially in following OEMs) to accumulate EV assets, and the dieselgate scandal in 2015 has also accelerated the competition among OEMs and pushed them to change their electrification strategies.

Therefore, in order to speed up 'electrification' and further EV promotion in the Japanese, Swedish, and German markets, introducing more aggressive regulations that incentivise OEMs to produce EVs. And it is also worth checking that both OEMs and the government I interviewed raised the impact on suppliers through the EV shift, thus innovation policy should focus on supporting the suppliers that depend on ICEVs today to shift their resources to new business, as well as focus on pushing OEMs by regulations.

5.2 Future research

The way of analysing EV assets of OEMs can be more elaborated. First, the last year I can observe the patents and prototypes of EV is 2017, but the influential events of the regulations are as recent as 2016, thus it is difficult to see the increase trend of EV assets of OEMs clearly. If one could add the data from 2018, I suppose that the trend would be seen well.

Second, indeed I researched the shift of EV assets from the change of the number of patents publication, if one could closely examine the detail of the patents with scientific professional glasses, he or she would find the change of the level of the patens. When I interviewed at the OEMs, I also asked how they viewed these results (Figure 4.1, 4.2, and 4.3). Toyota said 'Patent data reflects the technological asset directly. The tendency for the patent of solid-state battery seems to have three stages. First is the period before 2013, and in that period, many of the patents focused on the basic research level. Second is from 2013 to today. The patents mostly focus on developing research level. I predict that in future, as application level, the number of patents will increase as the third stage'. And Nissan said: 'It seems to react not to the regulations but the product life cycle. Around 2010, the number had been increasing for the launch of Nissan LEAF (at the end of 2010), and after that the activity had decreased. However, after around 2013 the patent activity has increased in order to improve products and prepare for next model change (the middle of 2017)'. Thus, one could find the shift of technological stage of EV assets by investigating closely the character of the patents.

Actually, I investigated deeply about some of the patents, and I found that the content of patent had been changing as I showed in Table 4.2. For example, the tendency of Toyota's patents about solid-state battery has shifted from component-level such as conductor and cell active material around 2011-2013, to system level such as the control device for the battery. This means that the asset has been developing from basic research level to practical applications. And as to Nissan, after the first shipment of EVs (Nissan LEAF), Nissan has applied patents related to advanced EV technologies like vehicle to grid system (needed for energy management services) and non-contact charging technologies. About the patent of Volvo cars and VW, both companies have not sold EV aggressively, you can see that there are two stages of the characteristics of patents. Though the patents did not focus on EV but electrification at first, they have published patents essential for EV.

To sum, not only the change of total number of the patents, but also the detection of the technological development of each patent, we may find when the EV assets of each OEM improved its development (e.g. basic research level to practical application level), and analyse the influence on the improvement by the regulations.

As mentioned as the conclusion, I suggest setting aggressive regulations as an effective way to transition to an EV-based society, but I have not described the concrete content of such regulations. It will be one future research field.

However, when governments plan to set such aggressive regulations, we also need to bear in mind that, as Unruh suggests, due to the increasing return of scale economies, non-optimal technologies are able to become locked in (Unruh, 2000). There are some articles indicating that large EVs with large lithium ion batteries emit much more CO2 when counted through product life cycles, taking into account the production process of lithium ion batteries and the portfolio of electricity generation (Ellingsen et al, 2016; Kieckhäfer et al, 2017).

The Minister of Sweden also mentioned during a media interview that we needed to reduce the total amount of CO2 throughout the whole vehicle's life cycle, for example reducing CO2 in the process of mining resources for batteries (The local se, 2018, online). That is, carbon emissions are involved in mining raw materials for batteries, such as cobalt, nickel, and lithium, and the impact on CO_2 reduction by EV driving differs to the ways of generation.

We need to consider deeply what kind of EVs and technologies are truly needed to reduce CO_2 and meet the large-scale goal to protect the Earth, and what kind of regulations would lead to the realisation of that goal. Therefore, when governments set the rule for technological transition, science-based discussions and assessment are needed to estimate the best way to reduce CO_2 from automobiles, including the point of view of the portfolio of generation, total life cycle emissions from vehicles.

Not just regulations, but well-considered regulations, are needed.

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Appendix

Questionnaire for each OEM

- What is the purpose of the latest business strategy for promoting EV?
- What do you think about the trend of EV assets of your company (Figure 4.1, 4.2, 4.3)?
- What do you think about the impact on job and profitability with the EV shift?
- What do you think about the influence on the business strategy by the trend of regulations?
- What is the expected governmental role for promoting EVs?

Questionnaire for the government

- How do you see the current trend of the regulations and OEMs’ business strategy?
- What is the expected governmental role for promoting EVs?