

Overcoming Barriers to Developing and Diffusing Fuel-Cell Vehicles: Governance Strategies and Experiences in Japan

Accepted manuscript (April 2020) in *Energy Policy*

<https://doi.org/10.1016/j.enpol.2020.111533>

Gregory Trencher¹, Araz Taeihagh², Masaru Yarime^{3,4,5}

1. Graduate School of Environmental Studies, Tohoku University, Japan

2. Lee Kuan Yew School of Public Policy, National University of Singapore, Singapore

3. Division of Public Policy, Hong Kong University of Science and Technology, Hong Kong

4. Department of Science, Technology, Engineering and Public Policy, University College London, United Kingdom

5. Graduate School of Public Policy, University of Tokyo, Japan

Abstract

To accelerate the electrification of road transport, numerous countries are promoting the diffusion of both Battery Electric Vehicles (BEVs) and Fuel-Cell Vehicles (FCVs). Both technologies hold unique advantages and disadvantages while also facing common barriers with regard to production and diffusion. Barriers may be classified into four categories: 1) supply-side (i.e. vehicle production), 2) infrastructure preparation (i.e. charging and fuelling), 3) demand-side (i.e. demand creation) and 4) institutional design. Relative to BEV literature, studies on FCV diffusion efforts are fewer. Also, while many studies highlight numerous diffusion barriers, knowledge on actual governance strategies to overcome these is lacking. Filling this gap, we examine governance measures used by government and industry in Japan to accelerate the development and diffusion of FCVs. The above framework is applied to examine coping strategies employed, unresolved challenges and potential ways to overcome these. Data are sourced from document analysis and expert interviews. Findings reveal robust measures to tackle supply-side and infrastructure challenges. Conversely, demand-side measures completely rely on public subsidies and lack regulatory measures to stimulate vehicle demand. Also, institutional strategies to increase the pool of FCV makers are lacking visible outcomes. We thus lay out several policy suggestions to overcome these unresolved challenges.

Keywords: fuel-cell vehicles (FCV); hydrogen; battery electric vehicles (BEV); barriers; diffusion;

policy

1. Introduction

As efforts grow around the world to accelerate the electrification of road transport in response to air pollution, energy security and climate change concerns, two key technologies are available for policymakers and vehicle manufacturers: battery electric vehicles (BEVs) and fuel-cell vehicles (FCVs). With each having zero tail-pipe emissions, both technologies are competing for political attention and public or private investments (Van de Kaa et al., 2017). In the short-term, BEV diffusion will clearly outpace FCVs. This is mainly due to immense global investment in charging infrastructure, rapid improvements in battery technology (and therefore driving ranges) and a continuously growing pool of BEV manufacturers and vehicle models. Nevertheless, FCVs can play a principal role in the transition to electric mobility due to several distinct advantages. These include rapid fuelling times, longer driving ranges and fewer concerns around battery deterioration and supply chain risks for cobalt (IEA, 2019). Furthermore, although hydrogen fuelling stations are expensive to build, once operational they can alleviate cost, space and congestion problems that follow the widespread installation of BEV chargers (Cano et al., 2018). Thus, with each technology holding specific advantages relative to the other, policymakers in many jurisdictions including Japan, China, Europe and the United States (US) are actively working to diffuse both BEVs and FCVs (Styczynski and Hughes, 2018).

Accelerating the diffusion of BEVs or FCVs is an immense governance challenge in terms of scale and complexity. The current global stock of BEVs (5.1 million) and FCVs (11,200)

is dwarfed by some 1 billion internal combustion engine vehicles (ICEVs) in circulation (IEA, 2019). Furthermore, a host of barriers are common to both BEVs and FCVs (Van de Kaa et al., 2017, Greene et al., 2014, Pohl and Yarime, 2012, Cano et al., 2018). On the vehicle production side there is a need to lower costs by spurring technological innovation. On the demand side there is a need to stimulate purchases despite high upfront costs and charging or fuelling inconveniences. Other pressing challenges include the provision of low-carbon fuelling/charging infrastructure and the difficulty of expediting or forcing the entry of incumbent ICEV manufacturers into the zero-emission vehicle (ZEV)¹ market (Steinhilber et al., 2013, Leibowicz, 2018, McDowall, 2016, Staffell et al., 2019). Tackling such barriers surpasses the capacity and resources of single organisations. Thus, collaborative governance strategies involving vehicle manufacturers, government agencies, infrastructure providers and energy producers (Yarime, 2009) are required to change market conditions and spur innovation and investments through regulation, economic incentives, public investment, target setting, institutional design and novel business models.

This paper focuses on the governance challenge of accelerating the development and diffusion of FCVs. Using empirical data from interviews and documents, we examine governance strategies formulated by government and industry in Japan to overcome a set of barriers that cover four perspectives: 1) supply-side (i.e. vehicle production), 2) infrastructure preparation (i.e. charging and fuelling), 3) demand-side (i.e. demand creation) and 4) institutional design (i.e. stimulating investment and the availability of technology). Our approach involves, firstly, identifying barriers from literature that are common to both

¹ We use the term zero-emission vehicle (ZEV) to refer to both BEVs and FCVs.

BEV and FCV and compiling these into an analytical framework, and secondly, applying this framework to examine coping strategies employed in Japan, intended effects, outcomes and unresolved challenges. Hence, the empirical findings of this study hold relevance not just to efforts to accelerate the production and diffusion of FCVs, but also BEVs.

Japan is particularly relevant for investigating efforts to diffuse FCVs. National government targets for on-road FCVs and fuelling stations (discussed in Section 2) are arguably the most ambitious in the world. Meanwhile, Japan is a world leader in fuel-cell development as measured by patents (Behling et al., 2015, Valovirta, 2018), government funding for research and development (R&D), and subsidies for vehicle purchases and infrastructure preparation (IEA, 2019). Additionally, the country is home to two of only three non-Chinese vehicle manufacturers currently making commercially available FCV sedans (Toyota and Honda). Japan's experiences therefore hold rich instructional value for policymakers in other countries attempting to diffuse FCVs.

This study makes several contributions to scholarship. First, much literature has examined the various factors hampering the market penetration of FCVs (Staffell et al., 2019, Hardman et al., 2017, Ball and Weeda, 2015, Cano et al., 2018, Saritas et al., 2019, Lopez Jaramillo et al., 2019). Yet there is a lack of empirical understanding into the nature and limitations of strategies formulated by government and industry to tackle these challenges. Second, while the US and Europe are well represented in FCV and hydrogen literature (Hodson and Marvin, 2007, Hardman and Tal, 2018, Decourt, 2019, Andreasen and Sovacool, 2015), dedicated studies on Japan have lacked. While scholars have investigated

public attitudes towards hydrogen fuelling stations (Itaoka et al., 2017) and R&D activities of FCV manufacturers (Haslam et al., 2012, Ishitani and Baba, 2008, Yarime et al., 2008), this is the first dedicated and detailed study on Japan's FCV diffusion strategies. Finally, from the perspective of sustainability transitions literature, there is growing interest in the role of regime-driven sustainability transitions (Geels, 2018, Ghosh and Schot, 2019). This study provides an exemplary case of this, given that the protagonists driving the transition to hydrogen mobility are regime actors such as state agencies and incumbent automobile manufacturers and fossil fuel suppliers.

2. Background to Japan's hydrogen society

With vehicle manufacturers conducting R&D into fuel-cells since the early 1990s (Yarime et al., 2008), collaborative efforts from Japanese government, industry and academia to commercialise and diffuse FCVs reach back to around the year 2000 (Haslam et al., 2012). For example, in 2001 a committee of industry, academic and societal experts collaborated with the Japanese government (the Ministry of Trade, Economy and Industry) to formulate an R&D and diffusion strategy for FCVs and fuelling infrastructure. The ambitious target of achieving 50,000 on-road FCVs by 2010 was missed due to production costs, technical hurdles and market immaturity (Ishitani and Baba, 2008). Despite a lack of early success, diffusion strategies have continued. In 2011, Toyota, Honda and Nissan formed an alliance with fuel suppliers and pledged to commercialise FCVs by 2015 (Haslam et al., 2012). This was mostly achieved, as Toyota released its long-awaited *Mirai* in 2014 and Honda followed suite with its *Clarity* in 2016. Meanwhile, although other manufacturers like Nissan, Mitsubishi, Mazda and Suzuki have previously released FCV prototypes (Ishitani and Baba, 2008), their ambitions to follow through with commercialisation remain unclear.

Although Japan's interest in FCVs can be largely explained by environmental and energy security concerns, regulation in overseas export markets—notably the Zero Emissions Vehicle (ZEV) mandate in California—have significantly influenced R&D activities in manufacturers like Toyota (Yarime et al., 2008). Meanwhile, the complexity and cost of FCV development provides Japan with a strategic means to protect its domestic vehicle manufacturing industry from rising competition posed from EV markets, where lower

technological hurdles are conducive to new entrants.

Japan's FCV diffusion efforts are occurring in the wider context of a national objective to realise a so-called 'hydrogen society'. This envisions using hydrogen in diverse areas including mobility, power generation and industrial processes (Nagashima, 2018, Trencher and Van der heijden, 2019, Valovirta, 2018). This ambition has been recently institutionalised into numerous but interconnected national policies and visions that bundle and reinvigorate historical fuel-cell and hydrogen deployment efforts. For example, the *Basic Hydrogen Strategy*, released in 2017, lays out Japan's basic vision of a hydrogen society and key areas for R&D and market development (METI, 2017). This strategy has since been embedded into the national *Basic Energy Strategy* (ANRE, 2018)—the most authoritative energy policy in Japan—and then operationalised into roadmaps (METI, 2019a, NEDO, 2017). These explicate priority areas for R&D along with multiple milestones for diffusion and cost/technical performance (see Table 1). Japan's vision for materialising a hydrogen society extends over several decades. It involves ambitious plans to source mass-produced hydrogen from overseas and stimulate consumption in both gas-fired power plants and transport.

Orchestrated by national government, powerful incumbent vehicle manufactures, fossil fuel suppliers and research institutions, the top-down nature of this transformational strategy is noteworthy. In contrast to more laissez-faire economies, this reflects Japan's history of state-led development and selecting technological winners for government support when formulating innovation policy (Haslam et al., 2012, Valentine, 2017).

Given its strategic national importance, national funding for hydrogen far exceeds other countries (IEA, 2019). Cumulative funding allocated over the past decade (2009-19) amounts to some \$3.78 billion², with most provided after the Fukushima nuclear disaster in 2011 (METI, 2019b). Meanwhile, a record budget of \$594.97 million was set aside for fiscal year 2019. This said, the majority of post-Fukushima budgets have focused on technology diffusion subsidies (fuelling stations, FCVs, stationary fuel-cells etc.) and demonstration projects (e.g. hydrogen production) (Nagashima, 2018). Budgets set aside for R&D are hence inferior to other countries. Given this, national policymakers have recently revised budgetary objectives to allocate larger future shares to R&D and better support basic research³.

² All dollars herein are US and have been converted from Japanese yen at the rate of 100 yen = \$0.94 (the rate on August 9, 2019).

³ This was information was given in a public address by a national policy maker from the Ministry of Economy, Trade and Industry (METI) at an industry forum 'Evaluation of Hydrogen and Fuel-Cell Projects and Challenge Sharing' held in Tokyo, June 17, 2019. Reflecting this shift, METI's energy budget for fiscal year al 2020 contains a new category of \$49.8 million to support basic fuel cell research.

Table 1 Key targets* for Japan's materialisation of a hydrogen society

	Current	2020	2030	Long-term	Current situation of conventional technology/fuel
Hydrogen supply					
Scale (tonnes/year)	200	4,000	300,000	5-10 million	85 million (natural gas imports)
Cost (\$/kg)	10 (at pump)	-	3	2	1.6 (natural gas import price, based on hydrogen's calorific value)
Production technique	Natural gas reformation, industrial by-product (from oil refineries etc.).		1) International supply chains using (i) fossil fuel + carbon capture and storage or (ii) renewable energy, 2) Domestic renewable energy		
Mobility					
Passenger vehicles (on-road)	4,000**	40,000 (and 200,000 in 2025)	800,000		62 million passenger vehicles (all types)**
Buses (on-road)	20	100	1,200		112,000 buses (all types)**
Forklifts (in use)	40	500	10,000		33,000 forklifts (annual domestic sales)**
Fuelling stations	134 (including 22 under planning or construction)*	160 (and 320 by 2025)	900	Replace gasoline stations	31,500 gasoline stations
Residential (cumulative sales)					
Fuel-cell co-generation (Enefarm)	336,000**		5.3 million		53 million households

Source: METI (2019a) with updates by author (when marked by **).

* Targets are set to be obtained by the end of each fiscal year (i.e. by March 31 the following year).

** Figures updated/obtained on March 2020 from various sources: (JADA, 2020); (FCCJ, 2020); (ACEJ, 2020); (JIVA, 2020). Numbers rounded for readability.

3. Methods

3.1 Study design and approach

Our basic approach consisted of 1) identifying in literature common diffusion barriers for BEVs and FCVs (as well as low-pollution vehicles like hybrids and compressed natural gas) and then 2) empirically examining governance measures employed in Japan to overcome these and spur the production and adoption of FCVs.

An analytical framework drawing largely on Steinmueller (2010) guides the literature review and empirical analysis. We also integrate insights from other scholarship on technology and vehicle governance to define four broad categories of barriers: 1) supply-side, 2) infrastructure preparation, 3) demand-side, and 4) institutional design. These four categories are then used as a basis for organising the various barriers reported in literature. When examining Japan's governance strategy, we focus on a narrower set of barriers that were found to be the most pressing and relevant to the case study. We thus omit from our analysis those that were not observed to be significantly hampering FCV production and diffusion efforts (See Table 2 and the discussion in Section 4). This approach allows a focused discussion on barriers and coping strategies that best reflect the current state of FCV production and diffusion efforts in Japan. As a limitation, however, this case study does not provide insights into potential coping strategies for other challenges reported in literature, which one might expect to become more significant in coming years as the scale of FCV diffusion grows.

3.2 Empirical data collection

Data are derived from semi-structured interviews and various grey literature such as policy documents, presentation materials and reports. Data collection occurred during February 2018 to March 2020. A total of 19 interviews with 32 respondents were conducted by the first author, mainly on-site and in Japanese (see Appendix). The two-year period for data collection provided a longitudinal perspective that aided identification of the most significant governance strategies employed as well as persistent or unresolved challenges. All interviews were recorded and transcribed. To ensure a diversity of perspectives, we targeted both governance actors (e.g. government agencies, automotive manufacturers and fuel suppliers) in addition to third-party experts such as industry thinktanks and academic researchers. We also interviewed government and civil society actors in Australia (in Latrobe Valley, Victoria) to increase understanding into local perceptions of Japan's efforts to import hydrogen derived from brown coal.⁴

⁴ Although other international supply chains in Brunei and New Zealand are also under consideration, we did not target actors in these countries since the supply chain from Australia is expected by government actors to supply the bulk of Japan's hydrogen imports in the coming years.

4. Analytical framework: Barriers to producing and diffusing BEVs and FCVs

Literature reports multiple barriers that we have summarised in Table 2 in accord with four categories of technology governance proposed by Steinmueller (2010). As mentioned, in carrying out the empirical analysis, it became apparent that some barriers are not yet exerting a significant hampering force on efforts to produce and diffuse FCVs in Japan. Thus, before discussing the analytical framework, three barriers omitted from the empirical analysis are briefly explained below.

The first concerns the need to ensure steady and environmentally sustainable supplies of crucial raw materials such as lithium, cobalt and platinum. As production volumes for BEVs or FCVs increase, so do the risks of supply shortages or price fluctuations due to dependence on a small number of producing nations. Similarly, environmental and human impacts are also expected to grow as mining activity expands (Sovacool et al., 2020). Given the currently limited production⁵ of FCVs in Japan, this issue is not proving a significant barrier at this point in time. This said, to reduce future risk, efforts are being made to reduce the volume of platinum required for fuel-cells and to establish an end-of-life recovery and recycling scheme. Second, car dealerships have been observed to constitute a major barrier to the adoption of BEVs (Zarazua de Rubens et al., 2018, Matthews et al., 2017). Principle reasons include a lack of on-display models and unbiased information on benefits and a general low motivation to sell BEVs to unfamiliar customers (since more

⁵ As of March 2020, cumulative sales for FCVs are limited to around 4,000 (see Table 1).

effort is required and low-maintenance requirements can reduce future income from services and repairs). Again, due to the limited volume of domestic FCV sales and low-reliance on showrooms (since most are booked in advance by government agencies and corporations), this point-of-sale issue is yet to prove a significant barrier. Third, and finally, the lack of public familiarity with FCVs (which requires public outreach and educational strategies) was not empirically observed to be a significant barrier. Thus, the governance challenges articulated below and then examined in the case study should be seen as a set of issues that are particularly relevant to this early life-cycle stage of technology development and market creation for FCVs.

Table 2 Framework for categorising common barriers to BEV and FCV production and diffusion

	Description	Examined in Japanese case?	Key literature
Supply-side			
<i>Production issues (cost and technological)</i>	How to decrease the production cost of vehicles and spur innovation to increase technical performance (e.g. reduce deterioration of components, increase driving range and safety etc.)?	Yes	Cano et al. (2018) Berkeley et al. (2017) Staffell et al. (2019) Ball and Weeda (2015)
<i>Security and sustainability of raw material supplies</i>	How to provide steady and environmentally sustainable supplies of crucial raw materials for technology producers such as lithium, cobalt and platinum?	No	Biresselioglu et al. (2018) Sovacool and Brossmann (2010) Sovacool and Ramana (2014), Sovacool et al. (2020)
Infrastructure			
<i>Establishment of low-cost and sustainable electricity/ hydrogen supply</i>	How to secure an uninterrupted, low-cost and environmentally sustainable source of electricity or hydrogen for charging/re-fuelling?	Yes	(Egbue and Long, 2012) (Hardman et al., 2017) (Biresselioglu et al., 2018) Ajanovic and Haas (2019)
<i>Establishment of fuelling/ charging infrastructure</i>	How to optimise the rollout of charging/fuelling stations in terms of construction/operating costs and location while decreasing investment risks?	Yes	Leibowicz (2018) Steinhilber et al. (2013) Berkeley et al. (2017) Staffell et al. (2019) Hardman et al. (2017)
Demand-side			

<i>Market segmentation and targeting</i>	How to segment and target the market (e.g. light/heavy duty, mass market/commercial fleets etc.) so as to achieve the highest level of demand and penetration possible?	Yes	Hardman et al. (2015) Morton et al. (2017) Liao et al. (2017)
<i>Societal demand creation</i>	How to stimulate demand in potential buyers despite various psychological barriers relative to ICEVs such as higher upfront costs, charging/fuelling inconveniences, concerns over reliability, and fewer models to choose from?	Yes	Cano et al. (2018) Matthews et al. (2017) Biresselioglu et al. (2018)
<i>Point of sale tactics</i>	How to increase the likelihood of purchases at the point of sale (i.e. car dealer showrooms) by drawing customer attention to BEV/FCV benefits?	No	Zarazua de Rubens et al. (2018) Matthews et al. (2017)
<i>Public awareness and acceptance</i>	How to increase awareness of the benefits of BEV/FCVs in the general public (inclusive of non-purchasers) and boost social acceptance and familiarity with the respective technologies?	No	Egbue and Long (2012) Berkeley et al. (2017) Itaoka et al. (2017)
Institutional			
<i>System-level coordination</i>	How to facilitate the entire system by removing institutional barriers to collaboration, innovation and cost reduction?	Yes*	Xu and Su (2016) Yarime (2009) Pohl and Yarime (2012) Taeihagh and Lim (2019)
<i>Stimulating investment and availability of technology</i>	How to influence the technological choices of incumbent vehicle manufacturers to encourage investments in BEVs or FCVs so as to increase the pool of manufacturers and the availability of vehicles and different models on the market?	Yes	Berkeley et al. (2017) Biresselioglu et al. (2018) Staffell et al. (2019)
* Although this is not addressed as a stand-alone issue, we cover efforts to reform safety regulations and standards to accelerate the establishment of fuelling stations and associate cost reductions in Section 5.2.2.			

4.1 Supply-side challenges

Governing the diffusion of BEVs and FCVs requires supply-side measures—sometimes called ‘upstream’ (Taylor, 2008) or ‘technology-push’ (Xu and Su, 2016) instruments. These target technology and knowledge suppliers (i.e. vehicle manufacturers and research institutions) to increase their capacity to produce and diffuse innovation (Steinmueller, 2010, Zhang and Qin, 2018) and reduce cost and technological hurdles. Governance measures might involve non-regulatory measures such as technical support and knowledge provision, public R&D programmes, financial incentives and human resource training (Steinmueller, 2010).

4.1.1 Production issues (cost and technical)

Manufacturing ZEVs is hampered by cost and technological challenges. Beginning with cost, since production volumes are still inferior to ICEVs, ZEVs are unable to benefit from economies of scale and the learning curves embedded in established production lines and parts supply chains (Hardman et al., 2017, Ball and Weeda, 2015, Greene et al., 2014). A key determinant of production costs is batteries in BEVs and fuel-cell stacks and hydrogen tanks in FCVs (Cano et al., 2018, Berkeley et al., 2017, Ajanovic and Haas, 2019).

Expensive materials in these components contribute to elevated costs; batteries require lithium and cobalt while fuel-cells and hydrogen tanks require platinum and carbon fibre (Staffell et al., 2019). Lowering vehicle production costs hence requires strategies to reduce the volume of these expensive materials while increasing production volumes to attain economies of scale (Cano et al., 2018).

In addition, ZEV manufacturers must contend with multiple technical challenges. Driving range and charging speeds are particularly pertinent for BEVs (Liao et al., 2017, Steinhilber et al., 2013, Greene et al., 2014). Since these are determined by the energy density and chemistry of batteries, there is a need to create smaller, lighter, denser and faster-charging alternatives to current lithium-ion technology (Cano et al., 2018, IEA, 2018). While FCVs are not as affected by driving range concerns, they share the need to create smaller, lighter and more energy dense components (i.e. fuel-cells). In addition, both vehicle types suffer from durability and safety issues and share a need to increase the durability and lifetimes of batteries and fuel-cells (Ball and Weeda, 2015) and reduce risks of fire or explosion.

Incumbent ICEV manufacturers have developed market competitiveness by tackling technological challenges mostly in-house. In contrast, upscaling the production of ZEVs

despite technological immaturity requires governments to play a facilitator role. This can be through identifying technological challenges shared by competing firms and then steering R&D activities towards the open provision of scientific knowledge and solutions (Pohl and Yarime, 2012).

4.2 Infrastructure challenges

Research on historically successful mobility transitions has shown that widescale infrastructure preparation is a precondition that must precede vehicle diffusion (Leibowicz, 2018). This concerns both charging/fuelling stations and the supply of electricity and hydrogen (Steinhilber et al., 2013, Berkeley et al., 2017, Kester et al., 2018, Staffell et al., 2019, Hardman et al., 2017). This category of infrastructure challenges builds on Steinmueller's (2010) conception of 'complementary factors', which refers to governance measures assuring the supply of supporting infrastructure to technology users.

4.2.1 Establishment of fuelling/charging infrastructure

Charging and fuel suppliers face risk and uncertainty when investing in new infrastructure for users since low vehicle adoption rates hamper profitability (McDowall, 2016).

Government subsidies are therefore required to lower construction and operation costs and mitigate investment risks during the initial period of market immaturity. Innovative measures are thus required to build profitable business models and share construction/operations costs and risks across both automotive manufacturers and infrastructure suppliers (Hardman et al., 2015).

4.2.2 Establishment of low-cost and sustainable electricity/hydrogen supply

Diffusion of both BEVs (Egbue and Long, 2012, Biresselioglu et al., 2018, Li et al., 2017) and FCVs (Hardman et al., 2017, Saritas et al., 2019) is hampered by consumer uncertainty around the sustainability (e.g. carbon emissions) associated with the electricity or hydrogen supply used. Today most BEVs use grid electricity that usually contains varying proportions of fossil fuel power. Meanwhile, most FCVs use hydrogen produced from the reformation of fossil fuels. The concept of ‘zero emissions’ is hence problematic since emissions are simply transferred in many cases from the road to power stations or hydrogen production facilities (Steinhilber et al., 2013). For BEVs, this problem can be overcome by supplying charging networks with renewable electricity. For FCVs, however, producing carbon-free hydrogen from renewable energy via either electrolysis or biogas reformation is prohibitively expensive relative to fossil fuel reformation (Ball and Weeda, 2015). Furthermore, the intermittency of renewable electricity constitutes another barrier to producing large-scale and steady supplies of hydrogen. Accelerating the diffusion of BEVs and FCVs therefore requires governance measures to secure reliable, affordable and carbon-free supplies of electricity or hydrogen (Ajanovic and Haas, 2019).

4.3 Demand-side challenges

This third category concerns governance measures aimed at vehicle users. This involves both demand creation and market entry strategies. While Steinmueller (2010) categorises this as ‘demand-side’, other scholars use labels such as ‘consumer-oriented’ and ‘market-oriented’ policies (Xu and Su, 2016) or ‘market creation’ and ‘technological pull’ (Taylor, 2008). Demand-side governance involves both decisions around market segmentation and

targeting as well as demand creation. The latter may involve economic incentives (i.e. subsidies and tax credits), regulations (e.g. mandated technological requirements or bans) or information provision (Yarime, 2009, Styczynski and Hughes, 2018).

4.3.1 Market segmentation and targeting

Attaining mass market penetration requires that governments and industry consider the optimal market segment to target and concentrate resources on during the early stages of diffusion (Morton et al., 2017, Liao et al., 2017). Broadly speaking, road transport can be segmented into various categories such as private vehicles or commercial fleets and light-, medium- or heavy-duty vehicles (Brand et al., 2017). Fleets may comprise of government or private organisations, while the individual market can be further segmented into various driving habits and psychological profiles (Morton et al., 2017). The lower cost and shorter driving ranges of BEVs make them more suited to the mass-market in urban settings and smaller vehicles. Conversely, the higher cost and longer driving ranges of FCVs are potentially suited to targeting wealthier users through ‘high-end encroachment’ strategies (Hardman et al., 2015) and long-distance or high-utilisation fleet operators with larger vehicle needs (IEA, 2019).

4.3.2 Societal demand creation

The creation of market demand for both BEVs and FCVs must contend with an array of psychological barriers that can hamper purchase decisions. These include an aversion to higher upfront purchase costs relative to ICEVs—even despite lower running costs (Cano et al., 2018, Matthews et al., 2017, Li et al., 2017), concerns over performance and reliability

due to unfamiliarity with the technology (Greene et al., 2014, Egbue and Long, 2012), and inconveniences due to underdeveloped charging or fuelling infrastructure (Biresseolioglu et al., 2018, Van de Kaa et al., 2017, Leibowicz, 2018, Lopez Jaramillo et al., 2019). Both monetary and non-monetary incentives are required to overcome these challenges (Bergman, 2019, Steinhilber et al., 2013). While most governments rely on consumer subsidies or tax credits to reduce purchase costs, road toll or road tax exemption and subsidised charging/fuelling can also stimulate demand by lower running and ownership costs (Li et al., 2017). Demand creation may also involve non-monetary incentives such as permitting usage of priority parking and high occupancy vehicle lanes (Styczynski and Hughes, 2018). Regulation can also be used. Notably, Chinese cities such as Beijing and Shanghai have adjusted regulatory schemes to allow unlimited daily use of vehicles or to give priority or discounted rates to ZEVs in licence plate lottery systems (Xu and Su, 2016).

4.4 Institutional challenges

The fourth category concerns the need for measures to influence the functioning of the entire innovation system to establish an overall environment that is conducive to the generation and adoption of innovation (Xu and Su, 2016). Scholarship mostly defines institutions as formalised ‘rules of the game’ and measures to optimise the speed and ease of diffusing new technologies such as the adjustment of standards and regulations (Yarime, 2009, Pohl and Yarime, 2012, Taeihagh and Lim, 2019). We expand this conception however to encompass strategies aiming to influence the behaviour and technological choice of vehicle manufacturers and also to promote cooperation and co-ordination between multiple public and private players (Steinmueller, 2010, Ahl et al., 2019). Relevant

governance instruments can involve information provision by promoting open innovation and sharing intellectual property or regulations that force an industry-wide shift towards ZEV production and investments.

4.4.1 Stimulating investment and availability of technology

The transition to electrified road transport requires that all incumbent vehicle manufacturers mobilise around the shared goal of shifting R&D and vehicle production towards ZEV technologies. Until this occurs, however, market penetration is hampered by a lack of availability and diversity of models to suit the varying preferences of purchasers (Biresselioglu et al., 2018, Staffell et al., 2019). BEV purchasers in many European countries can now choose from around 40-50 models, which are produced by most major vehicle manufacturers (Mathieu, 2019). Yet as recently as 2015, 80% of sales came from only five models (Berkeley et al., 2017). Conversely, the speed at which vehicle manufacturers are entering the FCV market is significantly slower. At present, the pool of non-Chinese manufacturers with commercially available FCVs is limited to Toyota, Honda and Hyundai. Furthermore, numerous obstacles can discourage incumbent ICEV manufacturers from entering the ZEV market. Due to accumulated knowledge and large historical investments in production lines and R&D programmes, they can suffer from path-dependency to ICEV technology (Yarime, 2009) and lack knowhow for mass-producing ZEV alternatives (Berkeley et al., 2017). To overcome such barriers, multiple governments are using technology forcing regulations to influence the behaviour of manufacturers and accelerate the production of BEVs and FCVs. California and China have set mandatory minimum production quotas for ZEVs while the European Union has

adopted CO₂ emission standards that also limit ICEV production (Wesseling et al., 2015, IEA, 2018). Meanwhile, countries such as France and the UK have announced years after which the sale of ICEVs will be banned (Meckling and Nahm, 2019). Additionally, vehicle manufacturers have also attempted to coax incumbent competitors to enter the ZEV. For example, in 2014 Tesla disclosed its BEV-related patents and requested that competitors do likewise to spur open innovation and joint-learning across the industry (Musk, 2014).

5. Findings

The following sections now apply the above framework to examine coping strategies developed in Japan to overcome these challenges and accelerate the development and diffusion of FCVs. Findings are summarised in **Table 4**.

5.1 Tackling supply-side challenges

5.1.1 Production issues (cost and technological)

The Japanese government (via the Ministry of Economy, Trade and Industry, and the New Energy and Industrial Technological Development Organisation) is employing three interlinked measures to help FCV manufacturers and knowledge producers overcome various cost and technical challenges: 1) target setting via roadmaps, 2) collaborative agenda setting, and 3) thematic R&D funding programmes. The intended effect of these strategies is to encourage the mass production of FCVs by supporting open innovation to decrease production costs and to improve vehicle performance.

First, government and industry have collaboratively produced roadmaps (METI, 2019a, NEDO, 2017) containing various targets to guide R&D and vehicle production regarding manufacturing costs, technical specifications and performance. Notable targets are summarised in **Table 3**. In particular, national policymakers highlight the importance of on-road FCV targets (40,000 by 2020, 200,000 by 2025 and 800,000 by 2030). These are intended as signals to domestic manufacturers that ‘the government intends to help you along (to meet the targets)’ so as to encourage investments to increase mass-production capabilities (int. #10). Other targets concern the production cost of vehicles and individual

components such as fuel-cell stacks and fuel tanks. These targets share the goal of lowering FCV production costs to attain price competitiveness with hybrid vehicles by around 2025 without subsidies. Finally, another set of targets concerns technical specifications and the performance of individual components. For example, two targets aim to halve the size of fuel-stacks and increase driving ranges to around 800 km by 2030, while decreasing platinum requirements. Although countries like China and the US have also fixed similar targets, ambitions to extend driving ranges and reduce system costs are notably stronger in Japan.⁶ Incidentally, targets for extending driving ranges and cutting fuel-cell system costs appear within reach. Toyota has reported that its second version of the *Mirai*, scheduled for sale at the end of 2020, will extend the current driving range of around 650-700 km (in JC08 mode) by around 30% (Toyota, 2019). This is principally through higher fuel-cell efficiency and fuel storage capacity. Meanwhile, media reports that this same model will cut the present system cost (i.e. fuel-cell and fuel tank) by around half (Nikkei, 2019).

Second, underpinning these targets are a host of technical agendas collaboratively identified through government mediated discussions between Toyota and Honda. Collaborative agenda setting reflects a broader resolve within government and industry to move vehicle manufacturers away from historical models of competition and secrecy towards cooperation and open innovation (int. #1,4,7,10,12). This shift towards open innovation was recently operationalised in the government mediated *Shared FCV Challenges Forum*, held in Tokyo in January 2019. Toyota and Honda were invited to collaboratively

⁶ For example, for driving ranges, China has only fixed a rough target of exceeding 500 km by 2025. Meanwhile, the objective for system costs in same year is \$128/kw, which is around two and a half times higher than Japan's target (\$47/Kw) (SAE, 2018).

present various technical issues hampering commercial production.⁷ Vehicle manufacturer respondents (int. #1,6) highlighted the novelty of this collaborative agenda setting approach and emphasised that without government mediation, traditional rivalry would have prevented this information exchange.

Table 3. Key technical performance and production cost targets in government roadmap* Source: NEDO (2017)

	Current	2020	2030	2040
Technical				
Driving range (km/5 kg hydrogen)	650		800	>1000
Fuel-cell output (kW/L)	3	4	6	9
Platinum usage (gm/kW)			0.05-0.1	0.03
Production cost				
System: combined fuel-cell stack and fuel tank (\$/kW)		< 75	< 38	19
Fuel-cell stack (\$/kW)		< 47	< 19	9.4

* Blank cells indicate the absence of targets for that year

Third, the government is linking thematic funding programmes to technical agendas collaboratively identified with industry, and then openly sharing the research results. In this strategy, issues are organised into two categories: (i) short-term, applied issues that each manufacturer should resolve independently (e.g. refining existing technologies or challenges related to vehicle assembly), and (ii) long-term, fundamental issues (i.e. new material development such as non-platinum catalysts) that merit tackling through government-backed open innovation (int. #4,7). In addition, several funding packages support the development of high-speed, mass-production technologies for components such as fuel-cell stacks and fuel tanks. This shift towards open innovation and government-assisted

⁷ As one example of the numerous challenges presented, both vehicle manufacturers have encountered the unanticipated observation that atmospheric pollutants such as sulphur are damaging fuel-cell catalysts.

R&D is largely necessitated by the cost and complexity of fuel-cell development.

Furthermore, a manufacturer (int. #12) explained that their historical reluctance to share information about emerging technologies with the government had resulted in public R&D agendas that were misaligned with their actual needs. Policymakers and vehicle manufacturers thus anticipate that the above-described shift towards collaboration and openness will better align public fund allocation with industry needs while accelerating the generation of solutions across scientific research institutions and parts suppliers (int. #7,10,12).

The above measures were deemed effective at increasing the technological capability of supply-side industries (int. #2,6). However, difficulties are being encountered in upscaling the volume of FCV production in line with roadmap targets, with the overall pace of FCV production falling behind initial expectations (int. #19). Indeed, there are currently only around 4,000 on-road FCVs in Japan (Toyota has produced around 90%) and the ambitious target of 40,000 by the end of fiscal year 2020 (i.e. March 31, 2021) will likely be missed. With Honda postponing the release and mass-production of the next generation of its current *Clarity* model (Newsweek, 2019), which is currently produced in limited volume, FCV production for the next few years will be increasingly dependent on Toyota. The latter has announced plans to increase the annual production of its *Mirai* as of late-2020 by around 10-fold, to around 30,000 units per year. (Toyota, 2018). One third of these would be for the domestic market.

Vehicle manufacturers, policymakers and experts (int. #6,12,16,19) highlighted three main

factors hampering mass-production. The first is a catch-22 issue whereby high costs have dampened mass-production ambitions. Consequently, limited production volumes are unable to lower costs through economies of scale. The second reason relates to supply chains. With FCV assembly involving a much larger network of component suppliers than BEVs, one manufacturer reported difficulty in securing the mass-production of parts such as air pumps, fuel injectors, fuel leak sensors and so on from upstream partners. The third factor concerns the technological complexity of mass-production. Given the vast number of individual fuel-cells and separators in each stack, the development of high-speed production methods is requiring more time than anticipated.

5.2 Tackling challenges related to infrastructure

5.2.1 Establishment of low-cost, sustainable hydrogen supply

Japan is employing three interlinked strategies to establish a mass supply of low-cost and sustainable hydrogen for the FCV market: 1) setting targets related to production volumes and cost, 2) aiming for economies of scale by integrating hydrogen into thermal power generation, 3) importing carbon-free hydrogen via international supply chains that utilise overseas fossil fuels and renewable energy. The intended effect of these strategies is to spur FCV diffusion by lowering fuel costs through mass-production and ensuring a steady, carbon-free supply of hydrogen.

First, the government has institutionalised ambitions to secure an affordable, mass supply of hydrogen through targets laid out in the *Fifth Basic Energy Strategy* (ANRE, 2018) and the *Hydrogen and Fuel Cell Roadmap* (METI, 2019a). These aim for an annual production of

around 300,000 tonnes of hydrogen by 2030 at a cost of \$0.28/Nm³ and then \$0.19/Nm³ thereafter. Achieving these targets would roughly allow hydrogen/fuel-cell cost parity with: (i) the calorie equivalent price of liquified natural gas and (ii) running costs in hybrid vehicles.⁸ The long-term objective is to produce some 5-10 million tonnes of hydrogen by around 2050. Putting these figures in perspective, domestic hydrogen production in 2018 (from fossil fuel reformation) was only 200 tonnes whereas the target of 300,000 tonnes in 2030 could support a fleet of 4.2 million vehicles.⁹ Given that government targets only call for some 800,000 on-road FCVs in this year, Japan's strategy of reducing hydrogen costs through mass-production triggers a need to create additional demand for hydrogen outside the transport sector.

Secondly, Japan is thus looking to the power sector—rather than heavy-duty transport—to create large-scale demand for hydrogen. Current ambitions are to blend hydrogen with natural gas in existing gas-fired power plants before gradually replacing all gas plants in the coming decades with specialised hydrogen units (METI, 2019a). This strategy is driven by the realisation that a single hydrogen power station could consume a far greater quantity of fuel than the transport sector could alone.¹⁰ This would in effect mimic the current natural gas market, whereby power stations consume the majority imported, thereby driving economies of scale and creating spillover benefits in the form of lower fuel prices for other consumers like households (int. #8).

⁸ In 2030, running costs targets for FCVs would translate to a 'pump' price of around \$3 per kilo of hydrogen. This would fill the tank of today's Toyota *Mirai* for roughly \$15.

⁹ This figure assumes an annual driving distance of 10,000 km and a fuel efficiency of 700 km for every 5 kg (i.e. one full tank).

¹⁰ For example, a single 1 GW power station burning pure hydrogen for a year would consume the entire volume of hydrogen aimed for in the year 2030 (i.e. 300,000 tonnes) (METI, 2019a).

Third, government and industry are currently collaborating to build hydrogen supply chains to enable the importation of cheap, mass-produced and carbon-free hydrogen from overseas. In parallel, the government is actively supporting R&D and numerous pilot projects that produce hydrogen from domestic renewable energy.¹¹ The overriding narrative, however, is that domestic renewable sources alone could never produce hydrogen on par with the above cost and production volume targets (int. #8). Thus, near-term efforts are focused on realising international supply chains. Three are currently under construction or planning: (i) hydrogen produced from gasified brown coal in Australia and carried in liquid form; (ii) hydrogen produced from reformed natural gas in Brunei (near Malaysia) and carried with organic hydrides (toluene); and (iii) hydrogen produced via electrolysis from renewable electricity (geothermal and hydro) in New Zealand. The first two require the sequestration of all CO₂ emissions during production into nearby geological repositories. This portfolio of supply chains involves varying locations, energy sources, production techniques and carriers. This exploration of various energy import pathways also reflects the principle of risk-hedging through diversification, which underpins Japan's national energy policy (ANRE, 2018).

Interviews (int. #10) and policy documents (ANRE, 2018, METI, 2019a) suggest that government and industry are placing the highest expectations in the mid-term on the commercial feasibility of importing liquified hydrogen from gasified Australian brown coal

¹¹ The most prominent pilot project for carbon-free hydrogen production is an electrolysis demonstration under construction in Namie, Fukushima. This facility will have an output of 10 MW—currently the largest in the world—and will supply hydrogen for transport and other uses in the 2020 Tokyo Olympics.

(HESC, 2019, HySTRA, 2019). A fully functioning pilot project involving hydrogen production, transport via ship, and combustion in a small power station is scheduled for completion by 2021. In the event this pilot was positively evaluated from a technical, economic and social feasibility perspective, this supply chain would then be scaled-up to supply the bulk of Japan's future hydrogen needs. Due to the economic significance of coal exports to Australia's economy, this project is propelled by significant political and financial support from Australia at the national and state level as well as the coal mining community in Victoria's Latrobe Valley (int. #14,20).

This said, public acceptance and economic factors may challenge efforts to materialise any supply chain reliant on fossil fuel coupled with carbon capture and storage (CCS). Even if carbon emissions are effectively avoided during production, public opposition observed in Australia on environmental grounds seems unlikely to diminish (int. #13,18).¹² In addition, as a broader socio-economic concern, anti-fossil fuel sentiments are increasingly visible in the public sphere while financial institutions in both Australia and Japan are increasingly hesitant to fund thermal coal projects (Trencher et al., 2020). Moreover, the economic rationale underpinning the capital-intensive and slow-to-build coal-to-hydrogen project in Australia will be increasingly challenged by the plummeting costs of renewables and electrolysis technologies (Chapman et al., 2017). For instance, Australian researchers predict that hydrogen production using renewable electricity and electrolysis (using polymer

¹² Notable reasons cited by interviewed residents opposing the project included concerns about: (i) coal fires and methane leaks if coal extraction was carried out at full-scale to achieve 2030 production targets, (ii) waste from coal gasification, and 3) ecological impacts on local marine eco-systems from shipping out of the liquefaction plant in Port Hastings.

electrolyte membranes) could roughly attain cost parity with coal and CCS by around 2025 (Bruce et al., 2018).

5.2.2 Establishment of fuelling infrastructure

Five notable governance strategies are being employed to expedite the establishment of fuelling stations and lower associated costs: 1) target setting for station installations and construction cost, 2) providing government subsidies, 3) establishing industry platforms to co-ordinate station funding, construction and operation, 4) reforming safety regulations, and 5) standardising station design. The desired effect of this suite of strategies is to spur vehicle adoption by accelerating the establishment of fuelling stations and decreasing construction/operation costs and investment risks for industry.

First, the Japanese government has adopted a strategy of rolling out infrastructure well ahead of vehicles and has set ambitious targets for fuelling station deployment (160 by 2020, 320 by 2025 and 900 by 2030). These targets translate to a ratio of around 900 vehicles per station, which is the minimum level deemed acceptable from a profitability perspective by fuel suppliers (int. #11,12). As of March 2020, 134 stations (including 22 under planning or construction) have been prepared (FCCJ, 2020). Although this indicates significant progress towards achieving the 160 target by the end of fiscal year 2020 (i.e. March 31, 2021), the above tally includes 39 truck-based mobile stations that serve multiple suburban or rural locations on a rotational basis. If considering this, the current number of fixed stations (operating or planned) falls to under 100.

Second, generous government subsidies are supporting the fuelling station rollout. National government assistance covers up to 50% of construction costs while many prefectures also cover the majority of the remaining out-of-pocket expenses and subsidise operating costs. Public subsidies are particularly important in Japan given that the average construction cost of a hydrogen station is around \$3.5 million (METI, 2019a)—around two times higher than American and European counterparts (Nagashima, 2018).¹³

A third strategy lies in a collaborative industry platform called JHyM. This mobilises automotive manufacturers (Toyota, Honda and Nissan), fuel suppliers (JXTG Energy, Iwatani etc.) and financial institutions around the goal of sharing investment risks and cost burdening and expediting fuelling infrastructure preparation. Conceived as a ten-year strategy lasting until 2028 (after which fuelling stations are expected to achieve profitability without subsidies), JHyM provides financial support to fuel suppliers from funds collected from annual membership fees, government subsidies, contributions from Toyota and Honda, and investment from financial institutions. Fuel suppliers are contracted to build and operate stations under their own brand but temporarily transfer ownership to JHyM in return for a steady revenue stream (int. #5). This arrangement creates several advantages. Fuel suppliers can sidestep the running costs associated with station ownership such as property taxes. Meanwhile, by assuming all administrative burdens in the network and collecting information from otherwise competing fuel suppliers, JHyM can cut management costs through economies of scale and by optimising operation procedures

¹³ There are multiple reasons for higher construction costs in Japan. The most important include: (i) tougher safety regulations for equipment and station design that require higher more expensive materials than abroad; (ii) a general tendency to build new stations (rather than retrofitting existing gasoline stations), which requires new land acquisition.

(int. #9).

A fourth strategy involves reforming a suite of 37 legal and safety regulations that are largely responsible for the elevated construction and operating costs of fuelling stations relative to other countries (METI, 2019c). Multiple respondents (int. #5,9,11) see Japan's current regulatory climate as excessively strict. Many regulations are governed by an outdated high-pressure gas law that requires longer-lasting materials and more frequent safety inspections and replacements than equipment in European and US markets. An industry respondent (int. #5) expressed confidence that reforming regulations around engineering specifications (e.g. permitted thickness and type of materials or usage lifetimes for pipes, hoses and other equipment) will allow domestic station builders to import cheaper equipment from overseas without having to modify these to domestic standards.

Finally, a fifth strategy involves the industry-wide standardisation of engineering protocols that guide station design. This strategy is also expected to lower construction costs, since engineering drafting during the design stage represents a significant proportion of construction costs. Industry-wide standardisation will thus alleviate the current trend of designing stations 'one by one and from scratch' (int. #4).

In particular, two issues are challenging Japan's strategy for rolling out fuelling stations. First, even if the targets are achieved, it is doubtful whether this number of fuelling stations would provide a meaningful degree of convenience (in terms of location and proximity to users) relative to the national network of some 31,500 gasoline fuelling

stations, which currently supports ICEVs. From their perspective as a vehicle manufacturer, one respondent (int. #12) expressed preference for a much larger number of fuelling stations. They explained, however, that fuel suppliers oppose increasing fuelling station coverage beyond present targets as this would decrease profitability. Industry and academic experts (int. #4,9,19) also underscored the need for more stations, suggesting that economics could be improved by: (i) building stations with a smaller fuelling capacity than the current norm¹⁴ (which would lower capital requirements); and (ii) aggressively exporting stations abroad to achieve economies of scale at home.

Second, interviews were particularly vocal about limited prospects for profitability in the short to mid-term. Fuel suppliers and investors acknowledged this by framing their role in supporting infrastructure as a ‘societal contribution’ (int. #9,11). One analyst (int. #4) explained that broader socio-economic trends such as population shrinkage, increased fuel efficiency in ICEVs and declining rates of vehicle ownership are dampening private sector interest in fuelling infrastructure investments—whether gasoline or hydrogen. Given the limited prospects for profitability, multiple independent experts (int. #2,4,19) argued that Japan should re-orient its fuelling station and vehicle diffusion strategy to high-utilisation commercial fleets that consume higher volumes of hydrogen and run on fixed, predictable routes (a point examined in Section 5.3.2).

5.3 Tackling demand-side challenges

¹⁴ Fuelling stations in Japan are generally built to supply around 300 Nm³ of hydrogen per hour at a pressure of 70 MPa. While these specifications allow each station to serve around 5-6 vehicles per hour and enable longer driving ranges (since more hydrogen can be stored in vehicle tanks), these norms increase construction and operating costs.

5.3.1 Market segmentation and targeting

Although Japan holds ambitions to diffuse commercial vehicles such as fuel-cell buses, forklifts and trucks, the initial market entry strategy is overwhelmingly focused on passenger vehicles for the masses. This strategy is explicitly visible in the national government targets for on-road FCVs, which far outweigh those set for buses and forklifts (see Table 1). For vehicle manufacturers and the government (int. #12,16), the intended effect of this strategy is to lower the production costs of key components (i.e. fuel-cell stacks and fuel tanks) through economies of scale. Since the production volume of fuel-cell buses or trucks is expected to remain limited, they argued that the highest cost reductions would occur if concentrating technological development firstly on private passenger vehicles and then integrating common components into buses and trucks. The focus on passenger vehicles also reflects the development trajectory of FCVs by Toyota, Honda and Nissan, which have all historically focused on sedans (int. #19).

This focus on mass-market passenger vehicles is also shaping Japan's strategy of deploying fuelling infrastructure. Instead of focusing on locations near highways and distribution centres (which would suit the needs of commercial or heavy-duty vehicle fleets), network planners are explicitly targeting potential private owners by building fuelling stations in urban areas with household incomes above the national average (int. #5,18). Japan's market segmentation and targeting strategy thus contrasts to other countries such as China, Germany and the US that are affording relatively more emphasis to fleet applications such as buses, trucks and forklifts (Kendall et al., 2017, SAE China, 2019, Staffell et al., 2019, Verheul, 2019).

Focusing the diffusion strategy on passenger vehicles for the mass-market must grapple with significant challenges. Despite ambitions to stimulate vehicle purchases from private individuals, the vast majority of the currently 4,000 on-road vehicles have been purchased by government agencies and corporations (#19). One vehicle manufacturer (int. #6) conceded: 'By targeting the passenger vehicle market, our opponent is the gasoline vehicle. Since this forces us to produce a relative advantage for both fuel and purchase costs, hurdles are incredibly high. But if we can't clear them, I doubt FCVs will ever diffuse in the future'. As an additional obstacle, industry analysts and academic experts (int. #2,4,19) voiced a shared concern that BEVs will likely serve the majority of private transport needs, given the relatively short average driving distances in Japan resulting from the limited landmass. They also problematised the need for large numbers of expensive refuelling stations when targeting the private passenger market. It was argued that the profitability of fuelling infrastructure could be improved if initial diffusion efforts were focused on: (i) commercial fleets of trucks and buses (which consume more hydrogen due to longer travelling distances), and (ii) strategically placing hydrogen stations for these vehicles along corridors such as highways and tollways.

However, several factors would likely hamper a vehicle diffusion strategy focused on commercial fleets. Firstly, Japan's capacity to produce fuel-cell buses and trucks is limited (int. #2,9,19). Efforts to commercialise light-duty trucks (principally via a partnership between Toyota and the convenience store chain 7/11) are still in their infancy while Honda's efforts to co-develop fuel-cell trucks with Isuzu (a domestic truck maker) have

also just begun. Meanwhile, only Hino (a subsidiary of Toyota) is making fuel-cell buses—albeit in limited volume. Secondly, although national and prefectural government agencies are attempting to spur the adoption of fuel-cell taxi and bus fleets by providing generous subsidies, quandaries related to fuelling infrastructure are hampering these efforts (int. #16,17). Buses require the construction of spacious and high-capacity fuelling stations, which have not been the focus of infrastructure rollout to date. Meanwhile, taxi fleet operators require stations operating on a 24-hour basis. These currently lack due to low utilisation rates resulting from the limited number of on-road FCVs. The likelihood of taxi and bus fleet operators switching to hydrogen is also reduced by a lock-in to present infrastructure. Many large bus operators have installed on-site diesel fuelling pumps. Additionally, for taxi fleets, FCVs have to compete against compressed-gas hybrid vehicles, which currently enjoy a well-established fuelling network in large cities like Tokyo. A final issue concerns running costs. Fuel-cell buses and taxis are unable to compete against the low fuel costs of conventional diesel and compressed petroleum gas/hybrid counterparts. Fleet operators thus lack an economic rationale to pursue their introduction.

5.3.2 Societal demand creation

Japan's principle strategy for fostering market demand for FCVs is through generous economic incentives administered directly to individual or commercial fleet purchasers. These aim to spur market adoption by slashing upfront purchase costs (currently around \$70,000)¹⁵ by around half, to a level comparable with BEVs and plug-in hybrids.

¹⁵ The Toyota *Mirai*, the most widely selling vehicle, currently retails for around \$70,000 in Japan. (Recommended manufacturer's price including sales tax as of February 2020. Calculated at 100 yen = \$0.94 [as per footnote 1]). Also, unlike California, vehicles are purchased outright rather than leased.

By far the largest incentive lies in subsidies from national and prefectural/city governments. For example, the national government subsidy provides around \$19,000 and \$19,500 to the Toyota *Mirai* and Honda *Clarity* respectively (NEV, 2019). In addition, prefectural governments such as Tokyo currently provide a further \$9,500 or so for each while some cities (e.g. Yokohama) provide further subsidies of around \$5,000. Tax exemptions then provide a further economic incentive. In the case of the Toyota *Mirai*, the national government acquisition tax is reduced by around \$1,700 as part of the national eco-car tax incentive programme. Additionally, two annual vehicle taxes are heavily reduced for the first year (Nagashima, 2018).

Numerous government, industry and academic respondents (int. #2,4,6,10,12,17,18,19) described Japan's principal approach for creating demand as heavily reliant on government subsidies. Pointing to an emerging need for additional measures, multiple respondents (int. #6,18) emphasised the importance of non-monetary incentives (e.g. priority parking or express lane usage)¹⁶ that would create ownership benefits beyond one-off economic savings. Respondents also underscored an eventual need for demand creation through regulation (int. #4,18,19). Many pointed to California's ZEV mandate (also emulated in China) as well as several Chinese cities, which prioritise licence plate allocation for ZEVs (via lotteries). The need for additional demand creation strategies is particularly apparent if considering running costs. Here, BEVs hold the upper hand by far. Owners can enjoy

¹⁶ Although some respondents commended the effect of California's policy to spur ZEV purchases by granting free use of high-occupancy vehicle lanes, they expressed equal awareness that the limited availability of lane space in Japan would prevent the adoption of a similar initiative.

unlimited usage of a nationwide network of some 30,000 chargers (which Nissan *Leaf* owners can access for a mere monthly membership of around \$19). Meanwhile, filling an FCV tank costs around \$47, providing a driving range of around 650-700 km. Even if cost targets are met for hydrogen production (see Table 1), FCV running costs would only fall to attain cost parity with hybrids. Underscoring this problem, a vehicle manufacturer respondent (int. #1) argued: ‘since there is no economic advantage to driving an FCV, it will probably only be environmentally conscious people who buy them’.

5.4 Tackling institutional challenges

5.4.1 Stimulating investment and availability of technology

In addition to the strategy of open innovation and the government mediated, joint identification of production issues (see Section 5.1.1), industry and government have attempted to encourage other incumbent vehicle manufacturers to enter the FCV market by: (i) sharing intellectual property; and (ii) setting a long-term target for ZEV production.

The first strategy involves the freeing-up of intellectual property. In 2015, Toyota adopted a decision to disclose and permit the royalty-free usage of 5,680 patents related to fuel-cell stacks, fuel tanks and fuelling infrastructure. This tactic aimed to accelerate the diffusion of FCVs and fuelling infrastructure by lowering economic and technological hurdles for both existing and potential entrants into the FCV market. A vehicle manufacturer respondent (int. #12) described the logic underpinning this strategy as follows: ‘Given the lack of (hydrogen) infrastructure, we believe the next 10-years should be an era of collaboration—not competition. Once infrastructure is prepared and technology matures, then

competition can start. (...) But competition can only happen once the number of FCV manufacturers and hydrogen stations increase to then drive vehicle diffusion to the point where consumers can purchase without any restrictions posed by a lack of infrastructure'. This respondent also explained that Toyota (like Hyundai) has an economic incentive to pursue this strategy, since they are actively working to sell fuel-stack systems to other makers (which encourages new market entrants by removing the need to develop in-house).

As a second measure, the Japanese government has attempted to accelerate the production of clean vehicles (i.e. non-ICEVs) and coax new market entrants by jointly formulating voluntary targets and commitments with vehicle manufacturers and related industries. The first attempt, in 2010, set the goal of achieving a combined 50–70% share of new vehicle sales in 2030 with hybrids, plug-in hybrids, BEVs, FCVs and clean diesel. A technology specific target called for a 3% share of FCVs. This strategy has since been reformed to a technology-neutral but also voluntary commitment called xEV. Formulated by a joint industry and government committee in 2018, this sets the goal for automakers to achieve a 90% reduction of well-to-wheel CO₂ emissions by 2050 through the increased production of BEVs, hybrids, plug-in hybrids and FCVs (NEV, 2018).

In terms of expanding the domestic pool of FCV producers, these strategies have had limited success. No incumbent manufacturer has newly entered the FCV market to accompany Toyota and Honda. Industry analysts speculate that the global shift towards BEVs has damped industry confidence in the diffusion prospects for FCVs (int. #2,4,19).

Indeed, although Nissan possesses the ability to produce FCVs and is actively involved in the preparation of hydrogen fuelling stations via JHyM (see Section 5.2.2), a domestic manufacturer (int. #12) postulated that Nissan's strategy has shifted entirely towards BEVs. Meanwhile, although Toyota is aggressively expanding its mass-production capability in preparation for the second-generation of its *Mirai*, as already mentioned, Honda has delayed both the release of its second-generation model as well any significant increase in the production volume of its *Clarity*¹⁷. Regarding this situation, multiple respondents emphasised that the technological complexity and cost of fuel-cell mass production is likely hampering both new market entries and the significant increase of current production volumes (int. #9,12,19).

Meanwhile, Toyota's efforts to coax new entrants to the domestic FCV market by sharing patents have also failed to bear fruit. An industry respondent (int. #12) explained that the majority of patent sharing and technology provision requests to Toyota are coming from bus and truck manufacturers in European and US markets. Here, CO₂ emission standards and minimum ZEV production mandates are driving new investments in the development of heavy-duty applications for fuel-cells. Although the Japanese government has responded to the increasing global momentum towards phasing-out ICEVs through the above-mentioned voluntary commitment for industry, this same respondent argued that the non-legally binding nature of this governance framework is insufficient to disrupt the short-term decarbonisation preference for hybrids and high-efficiency ICEVs by many vehicle

¹⁷ Since sales for *Clarity* began in March 2016, Honda has sold some 650 vehicles (including the plug-in hybrid model) for Japan's domestic market. In contrast, Toyota has sold over 3,350 *Mirai* vehicles since sales began in December 2014. Data from JADA (2020).

makers. Meanwhile, national bureaucrats (int. #10,16) also expressed awareness of an eventual need to debate the need for a regulatory strategy in Japan.

Table 4. Summary of Japan's governance strategies and unresolved challenges

Category and challenge	Specific strategies	Intended effect	Targeted actor	Unresolved challenges
Supply-side				
<i>1. Production issues (cost and technological)</i>	<ul style="list-style-type: none"> Setting shared targets for FCV sales, production costs and performance specifications. Promoting open innovation via collaborative agenda setting and solution generation (i.e. FCV makers share technological/cost problems and the government guides solution creation via thematic funding programmes). 	Spur the mass-production and market competitiveness of FCVs by lowering costs and improving the technical performance of vehicles.	<ul style="list-style-type: none"> Vehicle manufacturers Knowledge producers (industry/research institutes) 	<ul style="list-style-type: none"> Current volume of FCV production is insufficient to meet government diffusion targets.
Infrastructure				
<i>2. Establishment of low-cost, sustainable hydrogen supply</i>	<ul style="list-style-type: none"> Setting shared targets for volume and cost of hydrogen production. Committing politically to establishing a CO₂-free hydrogen supply. Constructing international supply chains for mass-produced, CO₂-free hydrogen. Utilising hydrogen in power generation (in place of natural gas) to drive demand and economies of scale. 	Spur vehicle adoption by lowering hydrogen fuel costs via the mass-production of CO ₂ -free hydrogen from overseas.	<ul style="list-style-type: none"> Industry (fuel suppliers and power generators) Overseas governments 	<ul style="list-style-type: none"> Societal acceptance of fossil-fuel derived hydrogen. Inferiority of FCV running costs relative to EVs, even if government targets for volume and the cost of hydrogen production are met.
<i>3. Establishment of hydrogen fuelling infrastructure</i>	<ul style="list-style-type: none"> Setting shared targets for hydrogen fuelling station installations. 	Spur vehicle adoption by accelerating the rollout of fuelling stations while	<ul style="list-style-type: none"> Industry (automobile manufacturers, fuel suppliers, financial institutions) 	<ul style="list-style-type: none"> Low attractiveness of FCVs due to an inferior network density of fuelling stations relative to BEVs and ICEVs.

	<ul style="list-style-type: none"> Establishing a joint-industry platform (JHyM) to construct and manage national network of fuelling stations. Reforming safety regulations for fuelling station components. Standardising engineering specifications in fuelling stations. Providing subsidies to fuel suppliers for construction and operation. 	<p>decreasing construction /operation costs and risks for industry.</p>		<ul style="list-style-type: none"> Restrained ability to provide a larger number of stations (which is desirable for vehicle manufacturers) due to the need to assure a profitable station-to -vehicle ratio for fuel providers.
Demand-side				
<i>4. Market segmentation and targeting</i>	<ul style="list-style-type: none"> Focusing on passenger vehicles for the mass-market. 	<ul style="list-style-type: none"> Lower the production costs of common components for passenger vehicles, buses and trucks (i.e. fuel-cell stacks and fuel tanks) by reaching economies of scale in the passenger vehicle market. 	<ul style="list-style-type: none"> Vehicle purchasers 	<ul style="list-style-type: none"> Targeting the private passenger vehicle market places FCVs in direct competition with BEVs (which have the upper hand in terms of running costs and charging convenience). Fuelling stations established for the private passenger vehicle market suffer from poor economics due to low-fuel demand relative to commercial fleets. Targeting commercial taxi or bus fleets is hampered by a lock-in to current diesel and compressed gas fuelling infrastructure and inferior running costs. Targeting buses and trucks is hampered by the limited production capacity of vehicle manufacturers and the need for purpose-built and high-capacity fuelling infrastructure.
<i>5. Societal demand creation</i>	<ul style="list-style-type: none"> Providing financial incentives (consumer subsidies and tax reductions). 	<ul style="list-style-type: none"> Stimulate mass-market consumer demand for FCVs. 	<ul style="list-style-type: none"> Vehicle purchasers 	<ul style="list-style-type: none"> Over-reliance on government subsidies for demand creation.

					<ul style="list-style-type: none"> • Need to create demand through other measures such as non-financial incentives and regulation.
Institutional					
<i>6. Stimulating investment and availability of technology</i>	<ul style="list-style-type: none"> • Sharing patents by Toyota. • Setting a common xEV vision for vehicle manufacturing industry to increase production of clean vehicles and reduce well-to-wheel emissions by 90% by 2050. • Promoting open innovation via collaborative agenda setting and solution generation (i.e. FCV makers share technological/cost problems and the government guides solution creation via thematic funding programmes). 	<ul style="list-style-type: none"> • Increase the number and availability of xEV (i.e. BEV, hybrid, plug-in hybrid and FCV) models and manufacturers. 	<ul style="list-style-type: none"> • Vehicle manufacturers 	<ul style="list-style-type: none"> • No new entrants in the FCV market. • Domestic vehicle manufacturers with FCV production capability are holding back investments for commercialisation (i.e. Nissan) and mass-production (i.e. Honda). 	

6. Conclusions and policy implications

This study examined governance strategies in Japan to accelerate the development and diffusion of FCVs. Our approach was firstly to identify hurdles common to both BEVs and FCVs from four perspectives (supply-side, infrastructure, demand-side and institutional) and then examine on-the-ground measures taken to overcome these. We thus filled a gap whereby barriers to FCV diffusion are widely reported in literature but empirical knowledge on actual coping strategies has lacked.

Overall, findings revealed a robust array of supply-side measures addressing production costs and technological challenges. For infrastructure, equally, multiple strategies are in place to accelerate the deployment of fuelling stations, reduce associated costs and establish a mass supply of low-carbon hydrogen. Conversely, multiple respondents problematised demand-side strategies. This most notably concerns the overwhelming focus on passenger vehicles for the mass-market and a deficiency of demand creation instruments beyond financial incentives. In addition, findings point to a need for renewed efforts to accelerate both the volume of FCV production and the pool of market entrants. With the bulk of production dependent on Toyota's *Mirai*, Japan will largely miss its 2020 target of reaching 40,000 on-road FCVs by the end of fiscal year 2020. Meanwhile, the scale of Honda's FCV production remains limited, with measures to entice other vehicle manufacturers into the hydrogen market through knowledge sharing and open innovation yet to produce tangible results. This situation will reduce Japan's ability to export large volumes of FCVs overseas. This will in turn hamper the speed by which other governments relying on vehicle imports from Japan such as California and Europe can

diffuse FCVs. Given the historical inability of Japanese government and industry to hit diffusion targets for on-road FCVs (Haslam et al., 2012), a new approach appears justified.

Policy implications here are threefold. First, given the technical complexity of producing fuel-cells inhouse and the immense cost and investment risks involved in building assembly lines, one meaningful strategy to lower FCV market entry barriers for vehicle manufacturers lacking historical expertise would be to nurture the formation of specialised fuel-cell makers for the vehicle market. This would eliminate the need for new entrants without in-house development capacities to source fuel-cells from their competitors (i.e. Toyota or Honda). This strategy would mirror measures in China that accelerate the entry of domestic vehicle manufacturers into the BEV and FCV market by outsourcing the development and supply of batteries and fuel-cells to common external platforms (Kendall, 2018, Kendall et al., 2017, Matsumoto, 2019). A second measure could facilitate the import of FCVs from overseas (e.g. from Korea and then elsewhere as new makers emerge). While allocating subsidies to imported technologies might be problematic, interviewed manufacturers and experts did not oppose this idea since it would accelerate market creation and increase vehicle choice. Third, introducing a technology-neutral regulation to mandate a minimum quota for ZEV production each year, like in California and China, could possibly increase manufacturer ambitions to produce FCVs. In addition to passenger vehicles, this might target trucks and buses—especially since the latter two require smaller numbers of fuelling stations and support better station profitability by virtue of their larger fuel consumption. As mentioned, California’s ZEV mandate has largely influenced the historical development of fuel-cell vehicles for Toyota and Honda

(Yarime et al., 2008) and continues to propel their ambitions to produce ZEVs today. While environmental policymaking in Japan is characterised by preferences for voluntary frameworks over stringent regulation, a shift towards forcing policies could simply involve mandating the current industry target of reducing well-to-wheel emissions for passenger vehicles by 90% by 2050, and then creating mid-term targets. This would disrupt the tendency of several manufactures,¹⁸ with relatively limited internal resources, to pursue short-term decarbonisation through the development of high efficiency ICEs.

Findings also revealed a need for additional demand creation measures. Although financial incentives are the global norm in spurring market penetration of ZEVs, these only provide short-term solutions due to their burden on fiscal systems. Meanwhile, non-monetary benefits like priority parking or express lane usage only offer benefits to early adopters before these limited resources reach maximum carrying capacity. As such, interviews revealed an awareness for demand-side regulatory approaches as a long-term solution. One approach might involve tackling the price inferiority of hydrogen relative to diesel and compressed-gas, which as observed, is disadvantaging the introduction of fuel-cell buses and taxis. This might involve reforming fuel taxes or creating market incentives to spur the retail of low-carbon alternatives like hydrogen (IEA, 2019). Again, California has notably employed this strategy via the Low Carbon Fuel Standard.

Japan's FCV diffusion efforts are focused on mass-market passenger vehicles. This approach counters a consensus amongst interviewed industry analysts, scholarship (Cano et

¹⁸ Two such manufacturers include Daihatsu and Suzuki.

al., 2018, Hardman et al., 2015, Meyer and Winebrake, 2009) and the International Energy Agency (2019) around the importance of firstly targeting fleets of long-range or high-utilisation vehicles. Focusing on the passenger vehicle market is risky. It places FCVs in direct competition with BEVs (where charging infrastructure is extensive and driving ranges are rapidly increasing) rather than niche applications where fuel-cells wield superiority by virtue of shorter fuelling times and longer driving ranges. Nevertheless, Japan's approach is not without advantages. As mentioned, targeting the mass-market carries the highest potential to drive down vehicle production costs through economies of scale. This will provide spillover benefits for countries hoping to import Japanese FCVs. Furthermore, while the business viability of Japan's fuelling station fleet is problematic in the short-term, in the long term, hydrogen fuelling infrastructure offers important but underappreciated cost and space advantages. For example, while around 400 refuelling stations could service a fleet of one million FCVs, a comparable fleet of BEVs would require around 10,000 fast-charging public stations and one million private stations (IEA, 2019).

Another finding with potential spillover benefits is Japan's approach to establishing a supply of mass-produced, low-carbon hydrogen from overseas. Undoubtedly, the current focus on sourcing hydrogen from fossil fuels combined with CCS must grapple with public acceptance challenges. Yet if any of the supply chains under investigation are successfully commercialised, this could initiate a new era of international energy trading with far reaching geopolitical consequences (IEA, 2019, Nagashima, 2018). For Asian countries reliant on fossil fuel imports, importing hydrogen derived from fossil fuel (coupled with

CCS) or solar would deliver benefits in terms of decarbonisation and enhanced energy security. More importantly, global hydrogen trading would allow energy producers like Australia and Saudi Arabia not only to survive—but also to *contribute to*— decarbonisation of the global economy.

Acknowledgements

The first author extends deep appreciation to the many organisations and individuals who kindly cooperated for interviews and provided data as well as Prof. Benjamin Sovacool for helpful insights during the planning stage. This study was supported by Kakenhi funds (grant numbers 17H06505, 19K20501 and 18H00919) from the Japan Society for the Promotion of Science.

Disclosure of interests

The authors declare no conflicts of interest.

References

- ACEJ. 2020. *Enefamū Meka Hanbai Daisu (Sales Volume of EneFarm Makers)*. In *Japanese*: [Online]. Advanced Cogeneration and Energy Utilization Center. Available: https://www.ace.or.jp/web/works/works_0090.html [Accessed March 5 2020].
- AHL, A., YARIME, M., TANAKA, K. & SAGAWA, D. 2019. Review of blockchain-based distributed energy: Implications for institutional development. *Renewable and Sustainable Energy Reviews*, 107, 200-211.
- AJANOVIC, A. & HAAS, R. 2019. Economic and Environmental Prospects for Battery Electric- and Fuel Cell Vehicles: A Review. *Fuel Cells*, 19, 515-529.
- ANDREASEN, K. P. & SOVACOOOL, B. K. 2015. Hydrogen technological innovation systems in practice: comparing Danish and American approaches to fuel cell development. *Journal of Cleaner Production*, 94, 359-368.
- ANRE. 2018. *Fifth Basic Energy Strategy* [Online]. Agency for Natural Resources and Energy. Available: https://www.enecho.meti.go.jp/en/category/others/basic_plan/5th/pdf/strategic_energy_plan.pdf [Accessed March 1 2019].
- BALL, M. & WEEDA, M. 2015. The hydrogen economy – Vision or reality? *International Journal of Hydrogen Energy*, 40, 7903-7919.
- BEHLING, N., WILLIAMS, M. C. & MANAGI, S. 2015. Fuel cells and the hydrogen revolution: Analysis of a strategic plan in Japan. *Economic Analysis and Policy*, 48, 204-221.
- BERGMAN, N. 2019. Electric vehicles and the future of personal mobility in the United Kingdom. In: JENKINS, K. & HOPKINS, D. (eds.) *Transitions in Energy Efficiency and Demand: The Emergence, Diffusion and Impact of Low-Carbon Innovation*. London and New York: Taylor and Francis, Earthscan.
- BERKELEY, N., BAILEY, D., JONES, A. & JARVIS, D. 2017. Assessing

the transition towards Battery Electric Vehicles: A Multi-Level Perspective on drivers of, and barriers to, take up. *Transportation Research Part A: Policy and Practice*, 106, 320-332.

- BIRESELIOGLU, M. E., DEMIRBAG KAPLAN, M. & YILMAZ, B. K. 2018. Electric mobility in Europe: A comprehensive review of motivators and barriers in decision making processes. *Transportation Research Part A: Policy and Practice*, 109, 1-13.
- BRAND, C., CLUZEL, C. & ANABLE, J. 2017. Modeling the uptake of plug-in vehicles in a heterogeneous car market using a consumer segmentation approach. *Transportation Research Part A: Policy and Practice*, 97, 121-136.
- BRUCE, S., TEMMINGHOFF, M., HAYWARD, J., SCHMIDT, E., MUNNINGS, C., PALFREYMAN, D. & HARTLEY, P. 2018. *National Hydrogen Roadmap* [Online]. CSIRO. Available: <https://www.csiro.au/en/Do-business/Futures/Reports/Hydrogen-Roadmap> [Accessed 5 June 2019].
- CANO, Z. P., BANHAM, D., YE, S., HINTENNACH, A., LU, J., FOWLER, M. & CHEN, Z. 2018. Batteries and fuel cells for emerging electric vehicle markets. *Nature Energy*, 3, 279-289.
- CHAPMAN, A. J., FRASER, T. & ITAOKA, K. 2017. Hydrogen import pathway comparison framework incorporating cost and social preference: Case studies from Australia to Japan. *International Journal of Energy Research*, 41, 2374-2391.
- DECOURT, B. 2019. Weaknesses and drivers for power-to-X diffusion in Europe. Insights from technological innovation system analysis. *International Journal of Hydrogen Energy*, 44, 17411-17430.
- EGBUE, O. & LONG, S. 2012. Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions. *Energy Policy*, 48, 717-729.
- FCCJ. 2020. *Commercial Hydrogen Station Information* [Online]. Fuel Cell Commercialization Conference of Japan. Available: <http://fccj.jp/hystation/#list> [Accessed March 3 2020].

- GEELS, F. W. 2018. Disruption and low-carbon system transformation: Progress and new challenges in socio-technical transitions research and the Multi-Level Perspective. *Energy Research & Social Science*, 37, 224-231.
- GHOSH, B. & SCHOT, J. 2019. Towards a novel regime change framework: Studying mobility transitions in public transport regimes in an Indian megacity. *Energy Research & Social Science*, 51, 82-95.
- GREENE, D. L., PARK, S. & LIU, C. 2014. Analyzing the transition to electric drive vehicles in the U.S. *Futures*, 58, 34-52.
- HARDMAN, S., SHIU, E. & STEINBERGER-WILCKENS, R. 2015. Changing the fate of Fuel Cell Vehicles: Can lessons be learnt from Tesla Motors? *International Journal of Hydrogen Energy*, 40, 1625-1638.
- HARDMAN, S., SHIU, E., STEINBERGER-WILCKENS, R. & TURRENTINE, T. 2017. Barriers to the adoption of fuel cell vehicles: A qualitative investigation into early adopters attitudes. *Transportation Research Part A: Policy and Practice*, 95, 166-182.
- HARDMAN, S. & TAL, G. 2018. Who are the early adopters of fuel cell vehicles? *International Journal of Hydrogen Energy*, 43, 17857-17866.
- HASLAM, G. E., JUPESTA, J. & PARAYIL, G. 2012. Assessing fuel cell vehicle innovation and the role of policy in Japan, Korea, and China. *International Journal of Hydrogen Energy*, 37, 14612-14623.
- HESC. 2019. *Hydrogen Energy Supply Chain* [Online]. Hydrogen Energy Supply Chain. Available: <https://hydrogenenergysupplychain.com> [Accessed 15 May 2019].
- HODSON, M. & MARVIN, S. 2007. Understanding the Role of the National Exemplar in Constructing 'Strategic Glurbanization'. *International Journal of Urban and Regional Research*, 31, 303-325.
- HYSTRA. 2019. *HySTRA - CO2-free Hydrogen Energy Supply-chain Technology Research Association* [Online]. Tokyo: Hydrogen Energy Supply-chain Technology Research Association. Available: <http://www.hystra.or.jp/en/> [Accessed August 11 2019].
- IEA. 2018. *Global EV Outlook 2018* [Online]. International Energy Agency. Available: <https://webstore.iea.org/global-ev-outlook-2018>

[Accessed 27 May 2019].

- IEA 2019. Future of Hydrogen. Paris.
- ISHITANI, H. & BABA, Y. 2008. The Japanese strategy for R&D on fuel-cell technology and on-road verification test of fuel-cell vehicles. *Making choices about hydrogen: Transport issues for developing countries*. New York: United Nations University Press.
- ITAOKA, K., SAITO, A. & SASAKI, K. 2017. Public perception on hydrogen infrastructure in Japan: Influence of rollout of commercial fuel cell vehicles. *International Journal of Hydrogen Energy*, 42, 7290-7296.
- JADA. 2020. *Nenryobetsu Hanbaidaisu Jyoyoshya (Passenger Vehicles Sales Figures by Fuel Type)*. In Japanese: [Online]. Japan Automobile Dealers Association. Available: <http://www.jada.or.jp/data/month/m-fuel-hanbai/> [Accessed 5 March 2020].
- JIVA. 2020. *Tokei Shiryo (Statistic information)*. In Japanese: [Online]. Japan Industrial Vehicles Association. Available: <http://www.jiva.or.jp/data.html> [Accessed 5 March 2020].
- KENDALL, K., KENDALL, M., LIANG, B. & LIU, Z. 2017. Hydrogen vehicles in China: Replacing the Western Model. *International Journal of Hydrogen Energy*, 42, 30179-30185.
- KENDALL, M. 2018. Fuel cell development for New Energy Vehicles (NEVs) and clean air in China. *Progress in Natural Science: Materials International*, 28, 113-120.
- KESTER, J., NOEL, L., ZARAZUA DE RUBENS, G. & SOVACOOOL, B. K. 2018. Policy mechanisms to accelerate electric vehicle adoption: A qualitative review from the Nordic region. *Renewable and Sustainable Energy Reviews*, 94, 719-731.
- LEIBOWICZ, B. D. 2018. Policy recommendations for a transition to sustainable mobility based on historical diffusion dynamics of transport systems. *Energy Policy*, 119, 357-366.
- LI, W., LONG, R., CHEN, H. & GENG, J. 2017. A review of factors influencing consumer intentions to adopt battery electric vehicles. *Renewable and Sustainable Energy Reviews*, 78, 318-328.

- LIAO, F., MOLIN, E. & VAN WEE, B. 2017. Consumer preferences for electric vehicles: a literature review. *Transport Reviews*, 37, 252-275.
- LOPEZ JARAMILLO, O., STOTTS, R., KELLEY, S. & KUBY, M. 2019. Content Analysis of Interviews with Hydrogen Fuel Cell Vehicle Drivers in Los Angeles. *Transportation Research Record*, 2673, 377-388.
- MATHIEU, L. 2019. *Electric surge: Car makers' electric car plans across Europe 2019-2025* [Online]. European Federation for Transport and Environment Available: https://www.transportenvironment.org/sites/te/files/publications/2019_07_TE_electric_cars_report_final.pdf [Accessed 10 March 2020].
- MATSUMOTO, A. 2019. Development potential of hydrogen fuel cell electric vehicles in China. Tokyo.
- MATTHEWS, L., LYNES, J., RIEMER, M., DEL MATTO, T. & CLOET, N. 2017. Do we have a car for you? Encouraging the uptake of electric vehicles at point of sale. *Energy Policy*, 100, 79-88.
- MCDOWALL, W. 2016. Are scenarios of hydrogen vehicle adoption optimistic? A comparison with historical analogies. *Environmental Innovation and Societal Transitions*, 20, 48-61.
- MECKLING, J. & NAHM, J. 2019. The politics of technology bans: Industrial policy competition and green goals for the auto industry. *Energy Policy*, 126, 470-479.
- METI. 2017. *Basic Hydrogen Strategy* [Online]. Japan: Ministry of Economy, Trade and Industry (Agency for Natural Resources and Energy). Available: http://www.meti.go.jp/english/press/2017/1226_003.html [Accessed 17 May 2018].
- METI. 2019a. *Strategic Roadmap for Hydrogen and Fuel Cells* [Online]. Ministry of Economy, Trade and Industry. Available: https://www.meti.go.jp/english/press/2019/0312_002.html [Accessed 9 August 2019].
- METI. 2019b. *Suiso Nenryo Denchi Senryaku Rodomappu: Keizaisangyosho no torikumi ni tsuite (Roadmap and Strategy for Hydrogen and Fuel-Cells: Initiatives by the Ministry of Economy, Trade*

- and Industry*). In *Japanese*: [Online]. NEDO. Available: <https://www.nedo.go.jp/content/100895058.pdf> [Accessed August 10 2019].
- METI. 2019c. *Suiso Nenryodenchi Senryaku Rodomappu (Strategy and Roadmap for Hydrogen and Fuel Cells)*. In *Japanese*: [Online]. Ministry of Economy, Trade and Industry. Available: <https://www.meti.go.jp/press/2018/03/20190312001/20190312001.html> [Accessed 10 June 2019].
 - MEYER, P. E. & WINEBRAKE, J. J. 2009. Modeling technology diffusion of complementary goods: The case of hydrogen vehicles and refueling infrastructure. *Technovation*, 29, 77-91.
 - MORTON, C., ANABLE, J. & NELSON, J. D. 2017. Consumer structure in the emerging market for electric vehicles: Identifying market segments using cluster analysis. *International Journal of Sustainable Transportation*, 11, 443-459.
 - MUSK, E. 2014. *All our patent are belong to you* [Online]. Tesla. Available: <https://www.tesla.com/blog/all-our-patent-are-belong-you> [Accessed August 10 2019].
 - NAGASHIMA, M. 2018. *Japan's Hydrogen Strategy and its Economic and Geopolitical Implications* [Online]. Paris: IFRI Centre for Energy. Available: <https://www.ifri.org/en/publications/etudes-de-lifri/japans-hydrogen-strategy-and-its-economic-and-geopolitical-implications> [Accessed 15 June 2019].
 - NEDO. 2017. *Technology Development Roadmap for Fuel Cells and Hydrogen (in Japanese)* [Online]. Japan: NEDO. Available: http://www.nedo.go.jp/library/battery_hydrogen.html [Accessed 12 May 2018].
 - NEV. 2018. *Strategy for diffusing the next generation vehicles in Japan* [Online]. Next Generation Vehicle Promotion Centre. Available: http://www.cev-pc.or.jp/event/pdf/xev_in_japan_eng.pdf [Accessed August 9 2019].
 - NEV. 2019. *CEV Hojyokin Taishyo Saishin Sharyo (FCV) (Subsidy Targets*

- for Clean Energy Vehicles*). In Japanese: [Online]. Next Generation Vehicle Promotion Center. Available: <http://www.cev-pc.or.jp/newest/fcv.html> [Accessed August 11 2019].
- NEWSWATCH. 2019. *Kyukyoku no ecoka da ga...Honda ga FCV jiki moderu no tonyu wo enki suru jijyo (The ultimate eco-car, but Honda postpones launch of the next-generation model)* In Japanese: [Online]. Available: <https://newswitch.jp/p/18312> [Accessed 10 March 2020].
 - NIKKEI. 2019. *Toyota Shingata no Nenryodenchishya o Kokai. Kyozoekukyori ha 3 Wari Mashi (Toyota Announces New Model of Fuel Cell Vehicle. Driving Range Increased 30%)*. In Japanese: [Online]. Nikkei Keizai Shinbun. Available: <https://www.nikkei.com/article/DGXMZO50865080Q9A011C1EB2000/> [Accessed 5 March 2020].
 - POHL, H. & YARIME, M. 2012. Integrating innovation system and management concepts: The development of electric and hybrid electric vehicles in Japan. *Technological Forecasting and Social Change*, 79, 1431-1446.
 - SAE CHINA. 2019. *Hydrogen Fuel Cell Vehicle Technology Roadmap* [Online]. Strategy Advisory Committee of the Technology Roadmap for Energy Saving and New Energy Vehicles, Society of Automotive Engineers of China. Available: <http://www.ihfca.org.cn/file/FCV%20Tech%20Roadmap.pdf> [Accessed 10 June 2019].
 - SARITAS, O., MEISSNER, D. & SOKOLOV, A. 2019. A Transition Management Roadmap for Fuel Cell Electric Vehicles (FCEVs). *Journal of the Knowledge Economy*, 10, 1183-1203.
 - SOVACOOOL, B., ALI, S., BAZILIAN, M., RADLEY, B., NEMERY, B., OKATZ, J. & MULVANEY, D. 2020. Policy Forum: Sustainable minerals and metals for a low-carbon future. *Science*, 367, 30-33.
 - SOVACOOOL, B. K. & BROSSMANN, B. 2010. Symbolic convergence and the hydrogen economy. *Energy Policy*, 38, 1999-2012.
 - SOVACOOOL, B. K. & RAMANA, M. V. 2014. Back to the Future: Small

Modular Reactors, Nuclear Fantasies, and Symbolic Convergence. *Science, Technology, & Human Values*, 40, 96-125.

- STAFFELL, I., SCAMMAN, D., VELAZQUEZ ABAD, A., BALCOMBE, P., DODDS, P. E., EKINS, P., SHAH, N. & WARD, K. R. 2019. The role of hydrogen and fuel cells in the global energy system. *Energy & Environmental Science*, 12, 463-491.
- STEINHILBER, S., WELLS, P. & THANKAPPAN, S. 2013. Socio-technical inertia: Understanding the barriers to electric vehicles. *Energy Policy*, 60, 531-539.
- STEINMUELLER, W. E. 2010. Economics of Technology Policy. In: HALL, B. H. & ROSENBERG, N. (eds.) *Handbook of the Economics of Innovation*. North-Holland.
- STYCZYNSKI, A. & HUGHES, L. 2018. Public policy strategies for next-generation vehicle technologies: An overview of leading markets. *Environmental Innovation and Societal Transitions*.
- TAEIHAGH, A. & LIM, H. S. M. 2019. Governing autonomous vehicles: emerging responses for safety, liability, privacy, cybersecurity, and industry risks. *Transport Reviews*, 39, 103-128.
- TAYLOR, M. 2008. Beyond technology-push and demand-pull: Lessons from California's solar policy. *Energy Economics*, 30, 2829-2854.
- TOYOTA. 2018. *Toyota moves to expand mass-production of fuel cell stacks and hydrogen tanks towards ten-fold increase post-2020* [Online]. Toyota Europe Newsroom. Available: <https://newsroom.toyota.eu/toyota-moves-to-expand-mass-production-of-fuel-cell-stacks-and-hydrogen-tanks-towards-ten-fold-increase-post-2020/> [Accessed 5 March 2020].
- TOYOTA. 2019. *Toyota to Unveil Next-Generation "Mirai Concept" at 2019 Tokyo Motor Show's "Future Expo"* [Online]. Toyota Global Newsroom. Available: <https://global.toyota/en/newsroom/toyota/29933463.html> [Accessed 5 March 2020].
- TRENCHER, G., DOWNIE, C., HASEGAWA, K. & ASUKA, J. 2020. Divestment Trends in Japan's International Coal Businesses. *Renewable*

- and Sustainable Energy Reviews*, 124.
- TRENCHER, G. & VAN DER HEIJDEN, J. 2019. Contradictory but also complementary: National and local imaginaries in Japan and Fukushima around transitions to hydrogen and renewables. *Energy Research & Social Science*, 49, 209-218.
 - VALENTINE, S. 2017. Modifying Recipes: Insights on Japanese Electricity Sector Reform and Lessons for China. In: CARROLL, T. & JARVIS, D. S. L. (eds.) *Asia after the Developmental State: Disembedding Autonomy*. United Kingdom: Cambridge University Press.
 - VALOVIRTA, V. 2018. *Case Study Report: Hydrogen Society (Japan)* [Online]. Brussels: European Commission. Available: http://www.jiip.eu/mop/wp/wp-content/uploads/2018/09/JP_Hydrogen-Society_Valovirta.pdf [Accessed 10 July 2019].
 - VAN DE KAA, G., SCHOLTEN, D., REZAEI, J. & MILCHRAM, C. 2017. The Battle between Battery and Fuel Cell Powered Electric Vehicles: A BWM Approach. *Energies*, 10, 1707.
 - VERHEUL, B. 2019. *Overview of hydrogen and fuel cell developments in China* [Online]. Holland Innovation Network in China. Available: Overview of hydrogen and fuel cell developments in China [Accessed 20 July 2019].
 - WESSELING, J. H., FARLA, J. C. M. & HEKKERT, M. P. 2015. Exploring car manufacturers' responses to technology-forcing regulation: The case of California's ZEV mandate. *Environmental Innovation and Societal Transitions*, 16, 87-105.
 - XU, L. & SU, J. 2016. From government to market and from producer to consumer: Transition of policy mix towards clean mobility in China. *Energy Policy*, 96, 328-340.
 - YARIME, M. 2009. Public coordination for escaping from technological lock-in: its possibilities and limits in replacing diesel vehicles with compressed natural gas vehicles in Tokyo. *Journal of Cleaner Production*, 17, 1281-1288.

- YARIME, M., SHIROYAMA, H. & KUROKI, Y. 2008. The strategies of the Japanese auto industry in developing hybrid and fuel-cell vehicles. *Making choices about hydrogen: Transport issues for developing countries*. New York: United Nations University Press.
- ZARAZUA DE RUBENS, G., NOEL, L. & SOVACOOOL, B. K. 2018. Dismissive and deceptive car dealerships create barriers to electric vehicle adoption at the point of sale. *Nature Energy*, 3, 501-507.
- ZHANG, L. & QIN, Q. 2018. China's new energy vehicle policies: Evolution, comparison and recommendation. *Transportation Research Part A: Policy and Practice*, 110, 57-72.

Appendix

Details of interviews (n=19)

Organisation	No. of respondents	Date
Government		
Ministry of Economy, Trade and Industry (METI)	3	15/3/2019
Ministry of Economy, Trade and Industry (METI)	3	3/7/2019
New Energy Development Organisation (NEDO)	1	3/4/2019
State Government of Victoria (Australia)	1	14/2/2019
City of Latrobe Valley (Australia)	1	11/2/2019
Tokyo Metropolitan Government (Bureau of Environment)	2	7/8/2019
Vehicle manufacturers		
Toyota Central Laboratories	1	1/2/2019
Toyota	1	5/7/2019
Honda and Honda Central Laboratories	2	28/3/2019
Fuel suppliers		
Iwatani	2	22/1/2019
Iwatani Tohoku Branch (Sendai)	1	2/7/2019
Japan H2 Mobility (JHyM)	1	7/3/2019
Heavy industry		
Kawasaki Heavy Industries	1	19/3/2018
Research institutes		
Japan Research Institute (Nihon Soken)	1	20/3/2019
Mizuho Research Institute	2	5/4/2019
Tama University	1	18/4/2019
Kyushu University (International Institute for Carbon Neutral Research)	1	10/2/2020
Musashino University	1	14/2/2020
Civil society		
Voices of the Valley (Australia)	6	12/2/2019
Total	32	