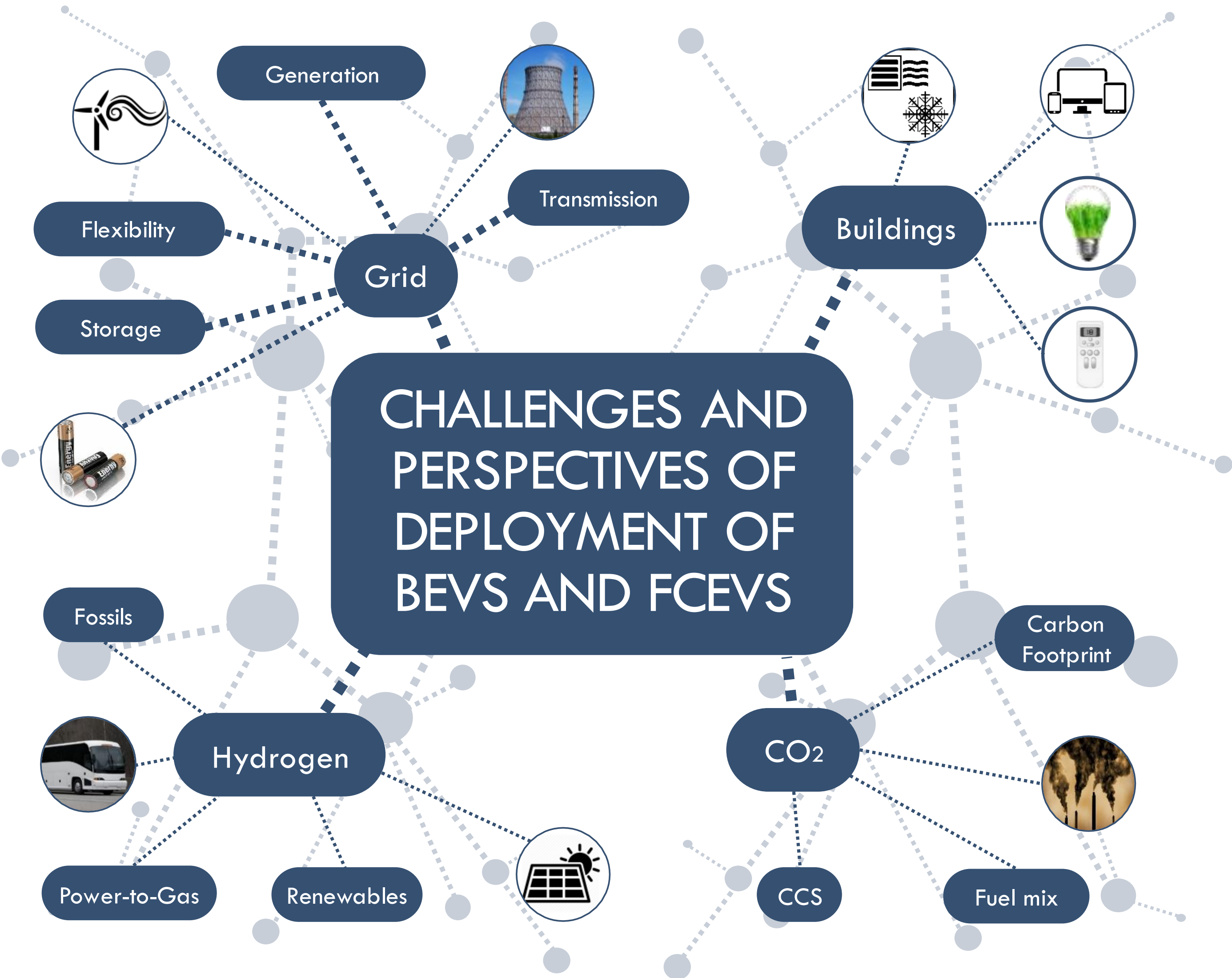
CHALLENGES AND PERSPECTIVES OF DEPLOYMENT OF BEVS AND FCEVS



APERC
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Challenges and Perspectives of Deployment of BEVs and FCEVs

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Foreword

Road transport is vital to APEC economies. With the exception of urban centres, the size and complexity of road networks make it extremely challenging to substitute other forms of transport in a manner that provides the same level of service and convenience. Road transport accounts for 83% of APEC transport energy demand. Given the size and extent of this sector, it must play a role in any decarbonisation effort. Advanced drivetrain technologies such as battery-electric vehicles (BEV's) and fuel-cell electric vehicles (FCEV's) play an important part in decarbonisation. Both technologies have received significant government support in many APEC economies. The switch to advanced drivetrain technologies offers many opportunities as well as challenges to integrate these vehicles into our electricity networks

This study seeks to identify the challenges facing these two technologies and potential solutions. When charging, BEVs can support intermittent renewable energy and provide other grid services such as frequency keeping. However, they also have a set of unique challenges. Battery storage capacity in BEVs is a limitation to vehicle mileage, requiring frequent and relatively long recharging time. In most cases, though these limitations only affect a small portion of a driver's travel, but this along with historically high capital costs, has slowed down BEV adoption. At their current technology level, FCEVs are able to store more energy, allowing for longer mileage than BEV's but come with their own set of issues, including the lack of refuelling infrastructure and difficulty sourcing cost-effective and low carbon fuels.

Dr. Kazutomo IRIE

President

Asia Pacific Energy Research Centre (APERC)

February 2020

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Executive Summary

The APEC region is the world's biggest automobile market both at present and in the foreseeable future. The way regional transport sector is decarbonised will have significant impact on the global energy demand and supply balance, greenhouse gas (GHG) emission as well as the automobile industry. By comparing the current deployment trend, government support, economic competitiveness, grid impact and integration, and the effect on CO_2 emission reductions of battery electric (BEV) and fuel cell electric vehicles (FCEV), this study attempts to draw insights on the region's road transport future decarbonisation.

At present the adoption of BEV is much higher than that of the FCEV. In the APEC region, as of 2017 the BEV stock reached nearly 1.6 million vehicles while FCEV stock was less than 6,000 vehicles, due to the higher cost of FCEV itself and its associated infrastructure. Both government support and the automobile OEM's[1] R&D[2] are also more focused on BEVs. In the APEC region more than 10 economies have implemented policies to support BEV adoption and seven economies have announced target roadmaps for BEV penetration, while only four economies have announced FCEV roadmaps. At present, only three FCEV models are available in the market, while the consumers have many more choices for BEVs.

For decarbonisation of the mobility sector, replacement of internal combustion engine vehicles (ICEVs) with BEV or FCEV using clean hydrogen (hydrogen produced from fossil fuels with Carbon Capture and Sequestration (CCS) or from water electrolysis using renewable electricity) on top of fuel economy improvement was found to result in overall CO_2 emissions reduction. However, if the hydrogen is produced from fossil fuel without CCS, the carbon footprint of a FCEV would be much higher than that of a high efficiency ICEV and BEV, thus replacement of an ICEV with a FCEV would result in increased CO_2 emissions.

When looking at the carbon footprint of a high efficiency ICEV, BEV, and FCEV, in all studied economies except China, an FCEV using hydrogen produced from renewable energy is less carbon intensive than high efficiency gasoline ICEV. And in several economies (Indonesia, the Philippines, and in some cases for Australia and China), where the CO_2 emission rate of power generation is high, a FCEV using renewable hydrogen is less carbon intensive than a BEV.

According to the analysis results (Chapter 4), in Canada, Japan, Korea, and the United States, where the carbon intensity of power generation is lower than in other economies, a BEV is the cleaner choice comparing with a gasoline ICEV and FCEV (using renewable hydrogen). However, in the remaining economies, a gasoline ICEV with improved fuel economy would be more effective in reducing CO_2 emission than a BEV.

BEV and FCEV can both contribute to the grid flexibility (e.g. "power-to-gas" (PtG)), though they interact with the grid in different ways. Several demonstration projects show that with proper management of BEV charging/discharging they will provide grid service. However, given the limited battery capacity of a BEV and the uncertainty associated with BEV's connection time to the grid, further scale-up of BEV adoption is necessary for the commercialization of vehicle to grid (VtG). At the early stage of BEV penetration vehicle to home (VtH) or vehicle to building (VtB) could be the practical form of BEV grid integration.

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[1] OEM = Original Equipment Manufacturer

[2] R&D = Research and Development

The interaction of a FCEV and its associated infrastructure with the grid is made through the Power to Gas (PtG) system, in which fluctuation of the grid could be balanced by hydrogen production and power generation by fuel cells. Since capacity of the PtG system is larger and the operation is more predicable than with a BEV, PtG is more effective in providing grid service than VtG. However, hydrogen production cost from water electrolysis using renewable power is still high. To further facilitate the commercialization of PtG, cost reduction and performance improvement of water electrolyzers, preferable grid service market regulations, as well as expansion of the hydrogen application market are necessary.

In the longer term, BEV penetration trend is expected to continue (IEA (2018), APERC (2016)). FCEV adoption will be at a slower pace due to not only the cost reduction of FCEV itself but also on the build-up and cost reduction of the whole hydrogen supply chain.

1 Introduction

Decarbonisation of the transport sector is crucial to reduce CO_2 emission because the sector is the second largest source of CO_2 emissions next to electricity and heat generation. The transition to clean energy in the transport sector is not as prevalent as in other sectors. Petroleum products are the dominant fuel in road transport, which is likely to persist for the coming decades. Utilising alternative fuels is vital to reduce CO_2 emissions from vehicles and electrification of vehicles will be crucial in this regard. The shift in road transport toward electric vehicles (EV) has already emerged globally, and the movement is being rapidly taken up in some economies. This trend will have implications for electricity demand and supply.

The report asses the effects of battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV) in terms of impact on the grid and on the decarbonisation. EVs includes BEVs, plug-in hybrid electric vehicles (PHEV) and FCEVs. BEVs are purely powered by electricity stored in on-board battery storage and FCEVs convert hydrogen to electricity for propulsion, whereas PHEVs have both an electric motor and internal combustion engine. PHEVs "use the electric battery as the primary energy source by relying on battery power for propulsion for a limited range 15 - 40 miles (25 - 65 km) before switching to internal combustion propulsion." Thus, PHEV is not studied in this report in that they still use gasoline.

Chapter 1 provides an overview of current situations and policy development of BEVs and FCEVs in the APEC region. Chapter 2 explains briefly vehicle-to-grid (VtG), presents a case study of VtG, and quantitative analysis of BEV/VtH impact on the grid and economic cost/benefit to the consumer. Chapter 3 looks at the risks and opportunities of power-to-gas (PtG) applications, focusing on the grid impacts and economics. Chapter 4 evaluates the CO_2 emission reduction effect of BEV and FCEV by quantitative analysis for selected APEC economies. Lastly, Chapter 5 provides comparative analysis of BEV/VtG/VtH and FCEV/PtG applications.

1.1 Current situation of battery electric vehicles in the APEC region

The EV market has grown rapidly, particularly after 2010, although the share of EVs remains small. Using the data from the International Energy Agency's latest report *Global EV Outlook 2018*, this section shows how many EVs have penetrated into the market in the APEC region.[3]

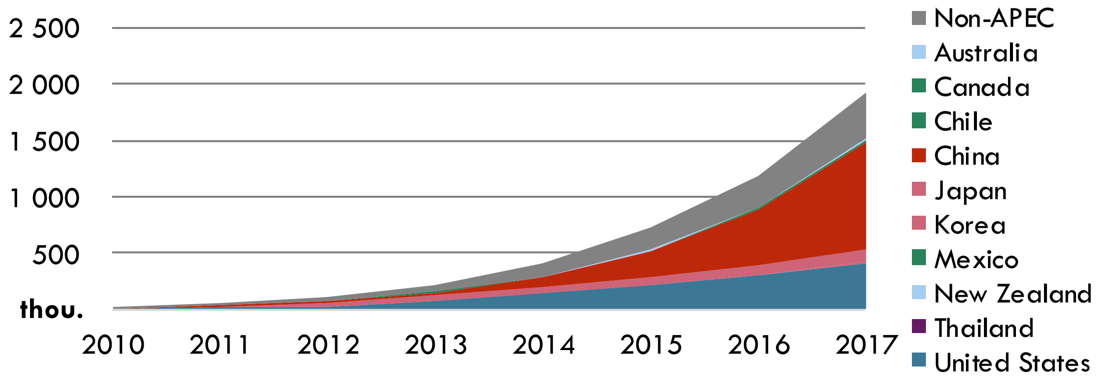
Comparing the BEV stock between 2012 and 2017, a substantial increase is observed worldwide (Figure 1-1). The global stock of BEV has increased from 0.11 million in 2012 to 1.9 million in 2017, in five years. The share of APEC in global BEV stock expanded from 69% in 2012 to 79% in 2017.

Particularly, China, the United States, and Japan represent three quarters of the world BEV stock. The growth of the BEV stock is outstanding in China, recording almost a 60-fold increase from five years ago and as of 2017, has close to the half of the global stock. The United States accounts for the second largest share with 401,550 BEV in 2017 although the annual growth rate has been slowing down. Japan follows the two big economies in the APEC region, but a continuously declining growth rate of BEV sales explains the reduction of Japan's share from 27% in 2012 to merely 5% in 2017.

While BEV stock is much smaller compared with the three economies mentioned above, some APEC economies show a high growth rate, implying that BEVs uptake is expected and could be accelerated in these economies. For example, the average annual growth rate of New Zealand, Canada, and Korea between 2012 and 2017 is 147%, 95% and 95%, respectively.

[3] IEA (2018), Global EV Outlook 2018: Towards cross-modal electrification, Paris: OECD/IEA

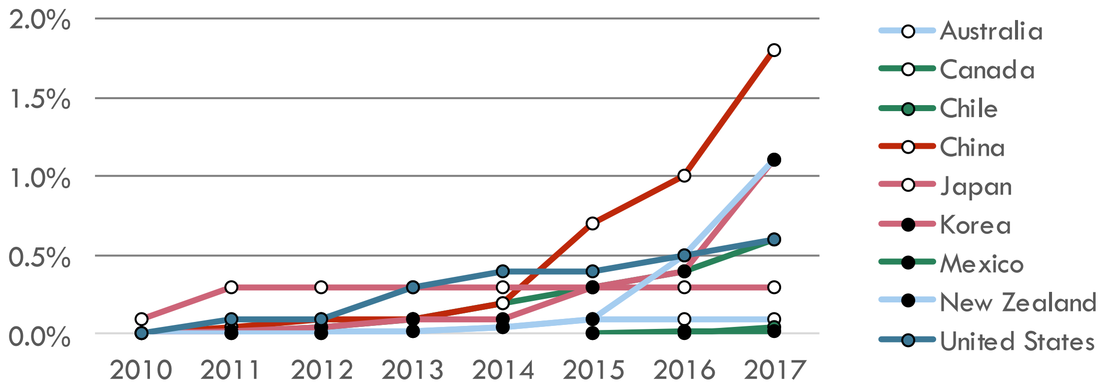
FIGURE 1-1. BEV STOCK, 2012 AND 2017



Source: IEA (2018)

Despite ongoing penetration of BEVs, the share that BEVs occupy in the vehicle market is marginal (Figure 1-2). In the APEC region, the highest market share is 1.8% in China, followed by 1.1% of Korea and New Zealand. The market share of these economies has surged for the last few years as shown in Figure 1-2. The United States and Canada show a gradual BEV market share increase. In other APEC economies, market share remains below 0.5%.

FIGURE 1-2. BEVS' MARKET SHARE OF THE APEC ECONOMIES, 2012-2017



Source: IEA (2018). Global EV Outlook 2018.

Electric vehicle supply equipment (EVSE) such as charging infrastructure has also been developed along with BEV uptake. This infrastructure is fundamental to encourage purchase of BEVs. EVSE is designed to provide alternating current (AC) and direct current (DC), and different power levels (Level 1, Level 2, and Level 3).[4] In addition, EVSE is differentiated by mode, according to the communication protocol between a vehicle and a charger.[5] EVSE includes private chargers where vehicles are plugged in on private property, usually at home or work, and public chargers that drivers could have access to at shopping malls, parking lots and on highways.

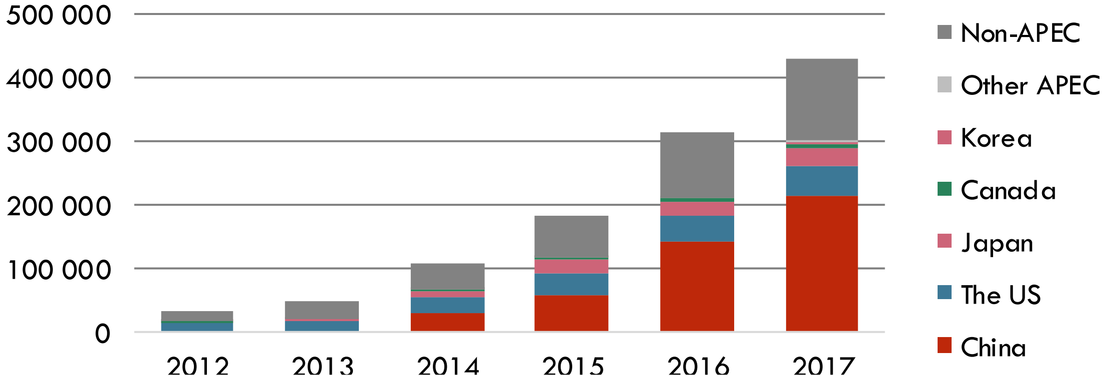
Since data on the private chargers are not available, IEA's data on the publicly accessible chargers is used to grasp the recent trend of EVSE. Figure 1-3 demonstrates that the public chargers have steadily increased. Among others, China shows a significant increase of publicly accessible chargers, accounting for approximately half in the world in 2017. China's policy direction to strengthen battery charging networks and infrastructure, which was issued in September 2015, accelerated the development of charging infrastructure. In addition, constraints on access to private chargers in dense

[4] Briones, A., Francfort, J., Heitmann, P., Schey, M., Schey, S., and Smart, J. (2012), 'Vehicle-to-Grid (V2G) Power Flow Regulations and Building Codes Review by the AVTA,' Idaho National Laboratory, pp.12-13

[5] IEA (2018), *op. cit.* p.41.

cities and the high utilization rate of non-private vehicles such as government fleets and taxis were loosened to make public chargers more available.[6] Similarly, relatively more public fast chargers per EV in Japan tend to help improve accessibility for people who live in multi-family residences in highly populated regions like the Tokyo Metropolitan area.

FIGURE 1-3. PUBLICLY ACCESSIBLE CHARGERS, 2012-2017



Note: Other APEC Economies include Australia, Chile, Mexico, and New Zealand.

Source: IEA (2018). Global EV Outlook 2018.

1.2 Policy support for EV deployment in the APEC economies

1.2.1 Monetary measures – subsidy and preferential tax treatment

Several policy measures have been implemented to encourage EV deployment in APEC economies. EVs are acknowledged to perform better in reducing CO_2 emissions compared with internal combustion engine vehicles (ICEVs), but the higher upfront cost is one of factors that prevent consumers from purchasing an EV. Fiscal measures including subsidy and exemption from tax and other fees are popular means to make the EVs more affordable.

Both central and provincial governments in China, Japan and Korea provide subsidies for consumers who purchase EVs[7]. Furthermore, in China and Korea, government has tightened standards for EV subsidies in early 2018. China's new standards that took effect in February 2018 raised the threshold of EV subsidy eligibility by setting higher technical standards:[8] (i) the minimum distance that vehicle travels on a single charge was extended from 100 km to 150 km, and (ii) the requirement for battery energy density was increased from 90 watt-hours per kilogram (Wh/kg) to 105 Wh/kg. These more stringent standards aim to foster research and development and encourage companies to manufacture vehicles that meet the technological standard in the global market.

In January 2018, Korea revised its subsidy program. Previously, 14 million won (US$12 000) for every purchased EV was offered until 2017[9]. Under the new system, the subsidy is differentiated by the vehicle's battery capacity with a range from 10.17 million won (US$9 000) to 12 million won

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[6] IEA (2018), *op. cit.* pp.45-47.

[7] In China, BEVs, FCEVs and PHEVs are categorized under new-energy vehicles (NEVs).

In Japan, subsidy is calculated as 1,000 yen (US$9) per kilometer driven on a full charge times a drive range, up to 400,000 yen (US$3,500). (Next Generation Vehicle Promotion Center (*in Japanese*))

[8] Bloomberg (2018, February 13, updated on February 14, 2018), 'China Raises Subsidies to Reward Longer Range Electric Cars'

[9] *International Financial Statistics Yearbook 2018* of International Monetary Fund is referred for exchange rates.

(US$11 000)[10]. A total of 240 billion won is allocated, enough to subsidize 20 000 vehicles on a first come, first served basis.

Favourable tax treatment is also available in the APEC region. In the US, a federal tax credit of US$2 500 to US$7 500 is available for a new EV purchased based on a vehicle size and battery capacity.[11] Some states (Louisiana, Maryland and Utah) provide tax credits, whereas New Jersey and Washington exempt EV from state sales and use taxes.[12] In Japan, EVs qualify for a tax break.

In the US and Canada, financial assistance is provided at the state level. In the US, California, Connecticut, Delaware, Massachusetts, New York, Pennsylvania, and Texas use rebates to encourage sales of clean vehicles.[13] In Canada, British Columbia has the Clean Energy Vehicles Program that includes a Point of Sale Incentive Program to make clean energy vehicles more affordable.[14] This program provides point of sale incentives of up to CA$5 000 (US$3 900) (with up to CA$1 000 additional for FCEV for fuelling) to a qualified purchaser or lessee of an eligible vehicle.

As one motivating incentive for clean vehicles, Hong Kong, China and British Columbia (Canada) have programs that offer the financial incentives to promote replacement of higher polluting or less efficient vehicles with EVs. The One-for-One Replacement Scheme in Hong Kong, China allows private vehicle owners who arrange to scrap and de-register their old private ICEV or EV and then register a new EV to receive a registration tax concession up to HK$250 000 (US$32 000).[15] Similarly, the BC Scrap-It program in British Columbia (Canada) sets out a list of incentives for vehicle owners who scrap an aging fossil-fuel powered vehicle in favour of cleaner forms of transportation. The list ranges from incentives of CA$6 000 (US$4 600) for a new EV and CA$3 000 for a used EV to a discount on a new electric bike (CA$850 off) and a mobility scooter (CA$600 off) and a CA$750 car share credit.[16]

1.2.2 Other monetary measures

There are other types of financial measures. In New Zealand, light electric vehicles are exempt from Road User Charges, which will save an average EV driver about NZ$600 (US$430) per vehicle annually.[17] In some major cities of China, preferential treatment is given to EV owners in getting a license plate, which is strictly controlled by local authorities. For instance, in Beijing, 60 000 out of 100 000 new car license plates issued every year are reserved for EVs.[18] Starting from 2018, the annual car license plate quota is reduced from 150 000 to 100 000, while keeping the EV quota at 60 000. This restriction makes allotment of license plates for ICEVs less available, which will result in taking years for an ICEV driver to get a license plate. Similarly, Shanghai, where license plates are

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[10] Korea Bizwire (2018, January 17), 'Electric Car Subsidies Subject to New Standards'

[11] Tesla and General Motors hit 200,000 total electric vehicles sold in the U.S. in 2018, reaching a threshold that triggers a phase-out of a federal tax credit in 2019.

[12] American Council for an Energy-Efficient Economy, 'Incentives for High-Efficiency Vehicles'

[13] Ibid.

[14] Clean Energy Vehicles for British Columbia, https://www.cevforbc.ca/clean-energy-vehicle-program

[15] Hong Kong, China, Environmental Protection Department, 'Promotion of Electric Vehicles in Hong Kong'

[16] The BC Scrap-It Program, https://scrapit.ca/incentivechoices/

[17] New Zealand Ministry of Transport, 'Electric Vehicles,' https://www.transport.govt.nz/multi-modal/climatechange/electric-vehicles/, this exemption is effective until 31 December 2021.

[18] China Daily (2017, December 15), 'Beijing limits new car plates, boosts new energy vehicles'

auctioned online to the public, waives license plate fees for EV drivers. This is quite attractive for drivers since a license plate costs more than US$14 000[19].

1.2.3 Non-monetary measures

Non-monetary incentives are also available in some APEC economies. In many states of the US, EVs are allowed to use high occupancy vehicle (HOV) lanes.[20] Parking is free for EVs in US cities such as Honolulu, Cincinnati, and San Jose. In some cities of China, EVs are free from traffic control measures that limit the number of vehicles on the road, for instance, based on license plate numbers.[21] Singapore where the number of vehicles is successfully controlled by the government demonstrates a unique case of EV promotion. In December 2017, a nationwide EV car-sharing program was launched under an agreement between the Land Transport Authority and the Economic Development Board, and BlueSG Pte Ltd, a subsidiary of Bolloré Group.[22] This program aims to deploy 1 000 EVs and 2 000 charging stations by 2020 and expects that these charging points will be the foundation for the economy's future EV charging infrastructure.

For China, encouraging EVs has an aspect of industrial policy as well as environmental policy. China puts priority on new energy vehicles (NEVs) to strengthen the domestic automaker and battery industry and make it competitive in the global market as well as to reduce CO_2 emissions.[23] For this purpose, China announced the NEV mandate policy, also known as the dual-credit policy, in September 2017 and it took effect in April 2018. Auto manufacturers are required to meet corporate average fuel consumption (CAFC) and NEV credit targets. The mandatory requirements on NEV credits are 10% of the conventional passenger vehicle market in 2019 and 12% in 2020, which have to be achieved by producing or importing NEVs or by purchasing of NEV credits from other manufactures. The minimum range for NEV credit qualification is set for BEVs, PHEVs, and FCEVs, and the number of NEV credits is specified based on driving range and vehicle curb weight.

Not only policy support given to drivers/consumers but also some measures to help producers are also important to boost EV deployment. Public procurement of EVs is widely adopted at the local level in APEC economies. Government procurement provides an opportunity to present the public with the benefits of shifting to EVs and to encourage auto industry EV production and infrastructure development. Also, funding for research and development (R&D) is necessary to advance technology and bring down costs of EVs. Specially, the cost of batteries is key to becoming competitive with ICEVs. Lastly, the target to be set is critical to expand EV deployment because a specified objective sends a clear message to the related stakeholders about the market. Table 1-1 shows the national target of EV deployment of APEC economies.

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[19] The Journal Gazette (2018, May 27), 'In China, electric cars rising in popularity'

[20] This incentive will expire on September 30, 2019 in some states such as Florida and North Carolina.

[21] Lu, J. (2018, February 28), 'Comparing U.S. and Chinese Electric Vehicle Policies,' Environmental and Energy Study Institute

[22] Economic Development Board(2016, June 30), 'Singapore launches Nationwide Electric Vehicle Car-Sharing Programme' and BlueSG (2017, December 12), 'BlueSG Launches Singapore's First Large-Scale Electric Vehicle Car-Sharing Programme Developed by the Bolloré Group'

[23] In June 2018, the National Development and Reform Commission and China Construction Bank announced a new $47 billion fund for high-tech industries including EVs. (The Wall Street Journal (2018, July 20), 'China Bets Big on Electric Cars')

TABLE 1-1. NATIONAL TARGET OF EV DEPLOYMENT OF APEC ECONOMIES

Economy	Target	Policy/Plan
China	- NEV sales: 2 million (2020) - 20% or more NEV share of 35 million vehicle sales by 2025	Automobile Industry Mid- and Long-term Development Plan (2017)
Indonesia	- EV stock: 2 200 (2025) and 4.2 million (2050)[24] - Electric Motorcycles: 2.13 million (2025) and 13.3 million (2050)	The Electric Vehicle Program
Japan	- EV and PHEV stock: up to 1 million (2020) - EV market share 20% - 30% (2030)	Roadmap for EVs and PHEVs toward the Dissemination of Electric Vehicles and Plug-in Hybrid Vehicles (2016)
Korea	2.2 million eco-friendly vehicles (10% of registered motor vehicles) by 2020	The Mid-term Strategies and Roadmap for Eco-friendly Motor Vehicle Distribution (2014-2020)
Malaysia	EV stock: 100 000 (2030)	National Electric Mobility Blueprint
New Zealand	EV stock: 64 000 (2021)[25]	
Thailand	EV stock: 1.2 million (2036)	Energy Efficiency Plan 2015-2036

Source: The Institute Energy Economics Japan

1.3 Current situation and policy development of FCEV in APEC

As of 2017, the global FCEV stock was 7 200 units, which is far less than BEV.[26] By economy, the US leads the market with 3 500 FCEVs, followed by Japan at 2 300. There are 330 hydrogen refuelling stations in operation worldwide.

FCEVs are supported by some APEC economies due to their potential to support low-carbon mobility. Support mechanisms include: research and development support, fiscal measures and deployment targets. The United States has put substantial efforts into hydrogen and fuel cell research development and demonstration (RD&D) since the early 2000s. The Department of Energy (DOE) Fuel Cell Technologies Office has led RD&D and innovation for transportation and diverse applications utilizing hydrogen and fuel cells.[27] "The Department of Energy Hydrogen and Fuel Cells Program Plan" was initiated in 2011 to conduct "comprehensive efforts to overcome the technological, economic, and institutional barriers to the widespread commercialization of hydrogen and fuel cells."[28] Currently, DOE has been working on an H2@Scale which is an initiative to enable low cost and large scale production and apply hydrogen across various sectors by utilizing variable renewable energy, nuclear and fossil fuels to avoid curtailment or stranded assets.[29]

[24] Sommeng, A. N. and Anditya, C. (2018, September 6-8), 'Boosting RE Power Generation in Indonesia Electricity Sector – A Policy Action by the Government,' presented at the 3rd International-Tropical Renewable Energy Conference (i-TREC) 2018 in Bali.

[25] New Zealand Ministry of Transport, *op. cit.*

[26] IEA (2018), *op. cit.*, p.20

[27] International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), 'IPHE Country Update: May 2018 – United States'

[28] U.S. Department of Energy (2011), 'The Department of Energy Hydrogen and Fuel Cells Program Plan,' p.6.

[29] IPHE, op. cit.

The United States has not set a national target on the number of FCEVs but some state governments have implemented regulations that specify a requirement for FCEVs production like California's Zero Emission Vehicle (ZEV) Regulation. In California, manufacturers are required to produce a number of ZEVs in terms of percent credits of sales, ranging from 4.5% in 2018 to 22% in 2025. There are other nine states that have adopted California's ZEV regulations.[30]

Aiming for realization of a hydrogen society, Japan has established two fundamental policy frameworks. First, the "Strategic Roadmap for Hydrogen and Fuel Cells" was approved in 2014 and revised in 2016. This roadmap laid out how Japan would be able to make use of hydrogen in three phases: significant expansion in hydrogen use in Phase 1, introduction of hydrogen power generation and establishment of large-scale hydrogen supply systems by the late 2020s in Phase 2, and establishment of a zero-carbon emission hydrogen supply system by the 2040s in Phase 3. The revised roadmap includes a specified target for FCEV deployment of 40 000 by 2020, 200 000 by 2025, and 800 000 by 2030.[31] Also, the target for the construction of hydrogen stations is set at 160 stations by 2020 and 320 stations by 2025. Second, in December 2017, Japan published a "Basic Hydrogen Strategy" which presents a policy direction for all government agencies to follow and regards hydrogen as a new carbon-free energy option, in tandem with the roadmap for introduction and deployment of hydrogen and fuel cell technologies.

China and Korea also have strengthened government support for the development of the FCEVs and infrastructure. Both economies encouraged cooperation between central and local governments, and private companies like automakers in order to become competitive globally.

In China, as one of NEVs, FCEV deployment is strongly supported by government. As of May 2018, there were approximately 710 FCEVs (60 vehicles, 150 buses, and 500 trucks) in China.[32] China stated in the 13th Five-Year Plan that the economy will promote R&D of fuel cells, build more hydrogen stations, and achieve mass production of FCEVs by 2020. China published the Energy Saving and New Energy Vehicle Technology Roadmap in October 2016 and its Chapter 4 is the Hydrogen Fuel Cell Vehicle Technology Roadmap.[33] In this roadmap, China sets the target for FCEV deployment at 5 000 by 2020, 50 000 by 2025, and one million by 2030. In February 2018, the "National Alliance of Hydrogen and Fuel Cell" was officially established, which is an interdisciplinary, cross-industry, interagency national alliance to help China's hydrogen and fuel cell technologies to achieve market maturity and international competitiveness.

Korea has also actively pursued building clean energy vehicles and creating business opportunities for local manufacturing industries. In April 2018, Korea's government and leading companies agreed to establish a network of 310 hydrogen filling stations nationwide by 2022.[34] Furthermore, in January 2019, Korea announced a hydrogen economy roadmap.[35] According to the roadmap, the number of FCEVs produced in the economy will reach 80 000 by 2022, 1.8 million in 2030 and 6.2 million in 2040. The roadmap also called for 1 200 hydrogen filling stations across the county by 2040. The

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[30] California Air Resources Board (2018), 'The Zero Emission Vehicle (ZEV) Regulation Fact Sheet'. Nine states are Connecticut, Maine, Maryland, Massachusetts, New York, New Jersey, Oregon, Rhode Island, and Vermont. Pennsylvania, Washington and Delaware have adopted California's Low Emission Vehicle standards.

[31] Japan Ministry of Economy, Trade and Industry of Japan (2016, March 22), 'Compilation of the Revised Version of the Strategic Roadmap for Hydrogen and Fuel Cells'

[32] IPHE, 'IPHE Country Update: May 2018 – China'

[33] Strategy Advisory Committee of the Technology Roadmap for Energy Saving and New Energy Vehicles and the Society of Automotive Engineers of China (2016), *Hydrogen Fuel Cell Vehicle Technology Roadmap* (English version)

[34] electrive.com (2018, April 25), 'Korea: public-private hydrogen station network'

[35] The Korea Herald (2019, January 17), 'Korea to produce 6.2 million hydrogen cars by 2040'

government will provide subsidies for fuel cell electric taxis and trucks, work with local governments to increase the number of fuel cell electric buses to 2 000 by 2022, and plans to start replacing all 820 police buses with fuel cell electric buses in 2021. Subsidies are expected to enhance production capacity and reduce costs by about a half to about 30 million won (US$27 000) by 2025.

Australia has designated hydrogen as an opportunity to develop an industry and export hydrogen to the global market, using the economy's extensive natural resources such as fossil fuels, solar and wind. In August 2018, Commonwealth Scientific and Industrial Research Organisation (CSIRO) published a "National Hydrogen Roadmap" to provide a blueprint of the development of a hydrogen industry.[36] A series of strategic investments along the value chain is needed to overcome major barriers to market activation, which are a lack of infrastructure and the cost of hydrogen supply. This roadmap identifies key priorities and areas for investment needed to make hydrogen commercially competitive with alternative technologies in each targeted application of hydrogen production, storage, transport, and utilisation.

Other APEC economies have also given consideration to application of hydrogen recently. For instance, in Malaysia, in July 2018, the Sarawak Energy Bhd (SEB) announced plans to build a pilot hydrogen production plant and refuelling station project to assess the viability of hydrogen and fuel cells in the transport sector.[37] The refuelling station will be the first in South East Asia. SEB was tasked by the state government to spearhead research in hydrogen fuel cell applications in 2017.[38] SEB will invest 15 million ringgit (approx. US$3.5 million) to produce 130 kg of hydrogen per day. The state authorities have ordered three hydrogen-powered buses from China. Sarawak plans to roll out these hydrogen buses in the state capital later this year.

In Indonesia, the Agency for the Assessment and Application of Technology (Badan Pengkajian dan Penerapan Teknologi, BPPT) and Toshiba Energy Systems and Solutions Corporation (Toshiba ESS), a leading supplier of integrated energy solutions of Japan signed a memorandum of understanding (MOU) in August 2018 on the promotion of autonomous hydrogen energy supply systems.[39] The off-grid integrated energy system uses "a renewable energy source to electrolyses hydrogen from water, and stores and uses the hydrogen in fuel cells to provide stable delivery of CO_2-free, environmentally-friendly electricity and hot water." Distributed energy resource system enhances the stability of energy supply and provides clean energy for isolated islands, mainly dependant on diesel.

The number of EVs and FCEVs in road transport is expanding. However, as shares increase challenges and opportunities arise. For EV these include the feasibility of integrating them into the grid and utilizing a vehicle on-board battery as energy storage. Automakers, utilities, and IT companies are developing business models that will facilitate smooth EV integration into the grid. Cost-effective and low-carbon production of (green) hydrogen from renewables remains a challenge for FCEV. The following chapters explore BEV and FCEV impacts on CO_2 emissions and grid.

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[36] Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., Hartley, P. (2018), *National Hydrogen Roadmap*, CSIRO, Australia

[37] Sarawak Energy (2018, July 29), 'Sarawak Energy Pilots Hydrogen Production Plant & Refueling Station for Transportation Sector'

[38] Sarawak Energy (2017, November 7), 'The Chief Minister of Sarawak's Media Statement on today's press conference on Hydrogen & Fuel Cell Research and press release'

[39] Toshiba Energy Systems & Solutions Corporation (2018, August 31), 'Toshiba and BPPT Conclude Memorandum of Understanding on the Promotion of Autonomous Hydrogen Energy Supply Systems in Indonesia'

2 Study of BEV impacts on electricity supply and demand

This chapter examines how and to what extent BEVs would affect electricity demand and supply. To cope with the rapid growth of BEV deployment, management of battery charging is vital to balance the power market. The first part lays out the relationship between BEVs and electricity demand/supply, focusing on the benefits and hurdles of applying vehicle-to-grid (VtG) systems. Then, some pilot projects are examined to understand VtG application and its impacts on the electrical grid. Lastly, BEV and VtG/VtH impact on the grid's the economic cost/benefit to the consumer are examined in detail by quantitative simulation.

2.1 Benefits and challenges of vehicle-to-grid (VtG)

2.1.1 Benefits of VtG

VtG is a system that enables bidirectional electricity flow between a vehicle and the grid and controls recharging and discharging of a vehicle battery when needed. VtG can be a useful tool when many vehicles are aggregated and operated properly, although each EV's power is very small. In VtG, each vehicle is connected to the grid and the system operator controls charging and discharging of the vehicle battery to balance the market. The aggregator service provider manages groups of vehicles to provide services to the electric utilities or system operators.

EV adoption contributes both to reduction in CO_2 emissions in many economy's and dependence on the petroleum products. Yet, that is not the only reason to incorporate VtG. It can also have significant benefits for both sides of electricity supply and demand. The benefits the VtG offer to the grid are described below.

2.1.1.1 Role as distributed energy resource

A major role anticipated for VtG is to function as a distributed energy resource or energy storage, which is especially critical as variable renewable energy such as solar and wind has increased in power generation. Because of their intermittent and unpredictable nature, these variable renewables have raised concerns about the impacts on the electrical grid. System operators and utilities look for flexible energy resources to reduce the uncertainty and variability of renewables to maintain grid stability. In general, EVs are parked most of the time and can be plugged into the power grid when they are not operated. The parked EVs enable the batteries of the vehicles to work as energy storage since they absorb surplus energy for the period of high power generation relative to low demand or release power back to the grid during the time when power generation is not enough to meet demand. Consequently, curtailment of intermittent renewable generation is lessened by using EV batteries. This function will be even more effective if batteries with bigger capacity are involved.

2.1.1.2 Shifting the load

VtG helps the load shift or load curve flatten through demand response/re-allocation. The time of peak demand for charging can be deferred from the evening hours to lower demand periods like midnight if the time of charging is controlled. Charging behaviour is likely to vary with lifestyle (for instance, whether or not, how often, and how far a vehicle is used to go to work or school), and with/without a time-of-use rate plan.

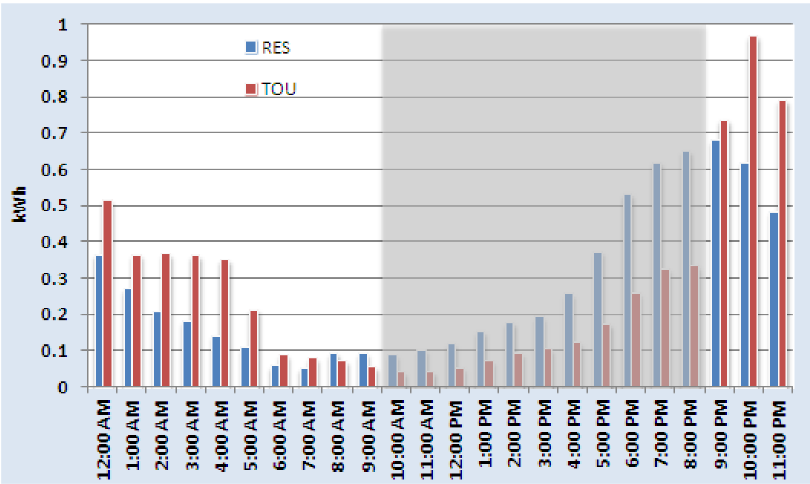
Many vehicle owners charge their vehicles when they arrive home from work either immediately during peak load hours or overnight during off-peak hours.[40] This indicates that the charging occurs at 18:00 – 6:00 in most cases. If numerous vehicle owners start to charge their vehicles at the same time upon arriving home in the evening more investment in distribution will be required to manage

[40] Briones et al. (2012). *op. cit.*, pp.23-24

the larger peak demand. Meanwhile, if overnight charging is used, the night-time load increases, which improves the average capacity factor of power system.

Figure 2-1 shows differences in charging patterns of consumers with/without time-of-use rate plans during summer weekdays. Power demand in the blue bar is indicated as RES (without time-of-use rate) increases significantly in the evening and peak at 9 pm. By comparison, power demand in the red bar shown as TOU (with time-of-use rate) is relatively low during the peak period coloured in grey and goes up substantially after the peak period because off-peak charging is cheaper. Where no time-based rates are available, the investment require to maintain a stable and reliable power supply may be high if excessive charging occurs during the peak period from the early evening to the late night. Since the time of charging is supervised through the VtG system, peak charging demand can be mitigated.

FIGURE 2-1. CHARGING PATTERNS DURING SUMMER WEEKDAYS AT PROGRESS ENERGY



Note: TOU - consumers with Whole House Time-of-Use Rate, and RES – other consumers. Peak periods are shown in grey.

Source: U.S. Department of Energy (2014)[41]

2.1.1.3 Provision of ancillary services

VtG can provide ancillary services that support the transmission and distribution systems such as frequency regulation and "spinning reserve"[42] frequency regulation immediately fine-tunes the balance of supply and demand within a short time frame (4 - 10 seconds).[43] A VtG system can influence the frequency in response to requests by the grid operators by regulating "up" or "down" by respectively exporting to or drawing power from the grid. Another related type of ancillary service is "spinning reserves" where VtG provides fast-response generating capacity on request from the system operator.[44]

2.1.1.4 Enhancement of power supply security

Improvement of power supply security is also a benefit that VtG could add. Working as distributed energy resources, VtG could be useful in case of an emergency such as a power failure. The US Department of Defence, for instance, finds national security advantages of microgrids or ancillary services through VtG in military bases to reduce vulnerability in the event of power outage or act of

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[41] U.S. Department of Energy(2014), 'Evaluating Electric Vehicle Charging Impacts and Customer Charging Behaviors – Experiences from Six Smart Grid Investment Grand Project. Smart Grid Investment Grant Program', p.11

[42] North American Electric Reliability Corporation (2012), 'Glossary of Terms Used in NERC Reliability Standards'

[43] Briones et al. (2012), *op. cit.*, p.7.

[44] The U.S. Energy Information Administration (EIA), 'Glossary – Electricity'

terrorism.[45] Independence of power infrastructure is vital for resilience in that the localized systems can be isolated from damage caused by problems on the grids.

2.1.1.5 Financial benefits

Last but not least, VtG has financial merits for both utility companies and consumers. Utilities could cut capital spending to build new power plants or upgrade existing infrastructure, which is necessary to cope with increasing electricity demand otherwise, because of the possible benefits of VtG mentioned above. Meanwhile, vehicle owners will receive revenues by selling power or providing ancillary services to the grid and benefit from fuel cost savings. A study that assessed the costs and benefits of EV adoption under California's Zero Emission Vehicle Program found that utility customers are better off from increasing EVs because there are positive net benefits to the utility, part or most of which can be shared with customers as reduced electricity tariffs.[46]

2.1.2 Challenges of vehicle-to-grid

While many potential advantages have been identified in VtG, it will not necessarily be easy to commercialize this new system with advanced technology on a large-scale because of the financial, technical, and administrative problems to overcome. This section raises major challenges for deployment of VtG. Specifically, barriers for infrastructure development, issues related to involvement of various stakeholders, technology development, and regulatory framework are described below to explain why VtG is not easy to apply.

2.1.2.1 Infrastructure development

Development of electric vehicle supply equipment (EVSE) is indispensable as more EVs enter the market. Especially, installation of public charging stations at appropriate places and intervals is essential to extend driving range. However, costs associated with EVSE can be an impediment to set up an EVSE at home or to increase the number of public chargers at non-residential locations.[47]

Three types of EVSE are typically used, that is, AC Level 1, AC Level 2, and DC Fast Charging, depending on supply power and charging time (Table 2-1). Among them, there are a wide range of costs associated with EVSE development, which can be affected by factors such as EVSE unit features and site locations.[48] These costs include charging station hardware costs, installation costs, and operation and maintenance costs and differ among types of EVSE. Charging station hardware is the dominant cost of a home charger, whereas installation costs have more impact on the cost of public charging stations.[49] Table 2-1 from a study by Smith and Castellano (2015) presents approximate cost ranges for EVSE units and installation, and reveals that installation costs are highly variable.[50] Installation costs include changeable factors such as labour costs and necessary materials and lead to great variability. Furthermore, VtG applications that require additional special features are likely to add extra costs in order to enable interaction between vehicles and the grid. As to VtG

[45] Briones et al. (2012), *op. cit.*, p.11.

[46] Ryan, N. E. and Lavin, L. (May 2015), 'Engaging Utilities and Regulators on Transportation Electrification,' *The Electricity Journal*, Vol.28, Issue 4, pp. 78-91.

[47] Most EV suppliers provide an AC Level 1 cord set with the vehicle but those who wish to have AC Level 2 speed or other features will have to pay extra.

[48] Parking garage installations are the easiest and most economical public charging stations. In comparison, curbside and surface lot stations tend to be more expensive than parking garage installations because they require trenching or directional boring to run conduit and wire to the station occasionally. (Rocky Mountain Institute (2014, April 29), 'Pulling Back the Veil on EV Charging Station Costs')

[49] Rocky Mountain Institute (2014), *Ibid.*

[50] Smith, M. and Castellano, J. (2015), 'Costs Associated With Non-Residential Electric Vehicle Supply Equipment - Factors to consider in the implementation of electric vehicle charging stations,' prepared by New West Technologies, LLC for the U.S. Department of Energy Vehicle Technologies Office, p.30

applicability, however, an AC Level 1 is not suitable. While it is equipped with the basic functions, its low supply power and lack of control or monitoring capabilities make it impractical to operate VtG.[51]

TABLE 2-1. EVSE COMPARISON BY CHARGING LEVEL

Charging level	Vehicle range added per charging time and power	Power supply	EVSE unit* cost range (single point), US$	Average installation cost (per unit), US$	Installation cost range (per unit), US$
AC level 1	$4\ \frac{\text{miles}}{\text{hour}}$ @ 1.4 kW $6\ \frac{\text{miles}}{\text{hour}}$ @ 1.9 kW	120 VAC/20A (12-16 A continuous)	300 - 1 500	N/A	0 - 3,000**
AC level 2	$10\ \frac{\text{miles}}{\text{hour}}$ @ 3.4 kW $20\ \frac{\text{miles}}{\text{hour}}$ @ 6.6 kW $60\ \frac{\text{miles}}{\text{hour}}$ @ 19.2 kW	208/240 VAC / 20 - 100 A (16 - 80 A continuous)	400 - 6 500	3 000	600 - 12 700
DC fast charging	$24\ \frac{\text{miles}}{\text{20 minutes}}$ @ 24 kW $50\ \frac{\text{miles}}{\text{20 minutes}}$ @ 50 kW $90\ \frac{\text{miles}}{\text{20 minutes}}$ @ 90 kW	208/480 VAC 3-phase (input current proportional to output power; ~20 - 400 A AC)	10 000 - 40 000	21 000	4 000 - 51 000

Note: *EVSE unit costs are based on units commercially available in 2015.

**The $0 installation cost assumes the site host offers an outlet for EV users to plug in their Level 1 EVSE cordsets and that the outlet already has a dedicated circuit.

Source: Smith and Castellano (2015). p.7, p.30

The governments of APEC economies have taken measures such as national targets and financial incentives to promote EVSE installations. For instance, China and Korea set a clear target for EVSE deployment. China aims to have 4.3 million private EVSE outlets and 500 000 public accessible chargers by 2020.[52] Korea plans to increase the number of EV fast-charging stations to 10 000 by 2022, a nearly four-fold increase from 2 531 in 2017,[53] which is comparable to the number of the economy's gasoline refuelling stations of 12 000.[54] In the US, various financial incentives are offered by the state governments to reduce the installation cost of EVSE.[55] In addition to the current measure to provide a subsidy for EVSE installation, Japan is considering relaxing regulations with an aim of revitalizing retailors' business and promoting vehicles running on alternate fuels. Small gas stations may be allowed to set up charging terminals alongside a gas pump, which are currently required to be about 10 meters apart, in fiscal year 2019 when the government intends to revise the regulations.[56]

[51] Briones et al. (2012), *op. cit.*, pp.13-15.

[52] IEA (2018), *op. cit.*, p.47.

[53] IEA (2018), *op. cit.*, p.117.

[54] Yonhap News (2018, February 2), 'S. Korea to invest 35 tln won in future vehicles in next 5 years'

[55] National Conference of State Legislatures (2017), 'State Efforts To Promote Hybrid and Electric Vehicles'

[56] Nikkei Asian Review (2018, February 21), 'Japan paves way for gas stations to charge up electric cars'

2.1.2.2 Technology advancement

Further technology advancement is needed to prove the usefulness of VtG operation. Among others, a vehicle battery is an important factor because it significantly influences the performance of EVs as well as VtG application. Improved battery performance such as extended range and longer battery life will enhance public acceptance of EVs. When it comes to VtG, however, consumers may be concerned about possibility of battery degradation if they participate in the VtG program.[57] Technology development to improve the capacity and cycle life of the battery is expected not only to facilitate penetration of EVs but also to help enable VtG application.

Equally, key technologies to be advanced are specific operating systems, equipment and devices for VtG to control and monitor EVs, EVSE, and the grid, and to enable communications between them. These technologies will allow the connected entities to be managed effectively. The vehicles need to be equipped with battery-management software and hardware for two-way flow of electricity, communication device between vehicles and distribution system operators, and EVSEs connecting vehicles to grid.[58] With VtG technology, the distribution system operators are able to program when and how long to recharge and simultaneously manage control of many vehicles while balancing electricity flow. In addition, advanced metering infrastructure (AMI) and sensing technologies are important for real-time energy management and to ensure grid quality and reliability, when the EVs are integrated into the grid.[59]

As much as the importance of technology development is recognized, cyber security has to be considered as well. Along with technology improvement, enhanced connectivity under the VtG program implies that power plants, the grid, EVSE, EVs, homes/workplaces are likely to be exposed to cyberattacks. The network of two-way flow of electricity is constantly monitored and controlled to optimize VtG operation through the use of data collected. The interactive network where monitoring and control of many devices are distributed will heighten risks that the computer systems and programming apparatus of enabling communications are penetrated. If operation and control systems of power plants and the grid become the target of cyberattacks, society and economic activity could be damaged enormously. Vehicle systems can be an easy entry point for cyberattacks due to accessibility of the vehicles.[60] This grave problem necessitates deliberate actions and appropriate countermeasures to protect all relevant components from a vehicle to the grid against cyberattacks. A fundamental measure to be taken are new mandatory standards for hardware and software. Also, monitoring cyber security will be vital and necessary although it may add extra cost.

2.1.2.3 Involvement of various stakeholders

To make VtG work, participation and cooperation will be requested of many parties including the electrical utility or grid operator, the automaker, the vehicle battery manufacturer, the EVSE provider, the vehicle owner, the workplace/commercial site owner, and the aggregation service provider. A fundamental but challenging step is to coordinate these multiple stakeholders, who have different purposes, some of whom may find no benefits in VtG operation. The utility companies and the vehicle

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[57] Karali, N., Gopal, A. R., Steward, D., Connelly, E., and Hodge, C. (2017), 'Vehicle-Grid Integration – A global overview of opportunities and issues,' Lawrence Berkeley National Laboratory and National Renewable Energy Laboratory, p.18; Briones et al. (2012), *op. cit.*, p.10

[58] Steward, D. (2017), 'Critical Elements of Vehicle-to-Grid (V2G) Economics,' National Renewable Energy Laboratory, p.1

[59] Markel, T., Meintz, A., Hardy, K., Chen, B., Bohn, T., Smart, J., Scoffield, D., Hovsapian, R., Saxena, S., MacDonald, J., Kiliccote, S., Kahl, K., and Pratt, R. (2015), 'Multi-Lab EV Smart Grid Integration Requirements Study – Providing Guidance on Technology Development and Demonstration." National Renewable Energy Laboratory, p. 21; "AMI integrates smart meters, communications networks, and meter data management systems and enables two-way communications by providing near real-time data on power consumption and electricity price."

[60] Karali et al. (2017), *op. cit.*, p.35.

owners will expect financial reward as mentioned above. The aggregation service providers and the EVSE providers may find business opportunities in ancillary services or demand side management. In contrast, it is uncertain whether the advantages and profits brought by VtG will be enough to offset the risks and costs the automakers and the battery industry encounter. For the automakers, VtG entails a design change to the vehicle and a bi-directional charger that will inevitably increase costs. Possible reduced battery life could also increase warranty costs.[61] Furthermore, VtG may heighten the risk of liability for the automakers. However, the automakers cannot make a vehicle with VtG functions more expensive than a level that consumers can afford to pay. Similarly, since the battery manufacturers may need to make substantial investment to improve battery performance and extend battery life, it might be challenging to meet the standards required.

Involvement of various stakeholders makes the VtG structure complex, thereby making responsibilities among them blur. Ambiguous roles could cause failures or result in duplicate work. Each stakeholder needs to be provided with well-defined obligations to facilitate efficient operation. For instance, specific contractual arrangements between vehicle owners and aggregation service providers can be helpful to comprehend what to do properly and to maintain commitment of the parties.

Lastly, the VtG program needs to be designed to ensure benefits for the consumers. The vehicle owners expect enough compensation for allowing the operator to use their vehicles to provide services as requested while retaining personal preference over when to use the vehicle. The popular means are up-front incentives and reduced electricity payment such as a time-of-use rate. Requirements for VtG such as plugged-in time and potential owner's loss of vehicle use must be carefully balanced against the needs of the utilities and the system operators.[62]

2.1.2.4 Regulatory framework

A regulatory framework will help create an enabling environment for the VtG application. It is important to adopt unified codes and standards regarding vehicles, residences/buildings, electricity business, communication, and EVSE, which are traditionally developed individually and vary widely by region (in case of the US) and by economy. Criteria related to VtG operation are yet to be developed properly because current standards have not probably considered two-way flow of electricity, the trend toward the EV deployment and the relatively new penetration of intermittent renewable energy resources. Various standards across regions make manufacturers inefficient if they have to comply with each regulation. The codes and standards need to be revised or created to validate VtG and improve quality and security of VtG operation.

2.2 Case study of VtG

Various demonstration/pilot projects on VtG application have been conducted globally and are particularly active in economies where EVs deployment is relatively high. This section looks at four demonstration projects in the US and Japan which are quite different in project scale and methodology. A brief description of each project is provided, followed by implications drawn from these cases to explore the possibility of VtG application.

[61] Briones et al. (2012), *op. cit.*, p.10

[62] Steward (2017), *op. cit.*, p.8

2.2.1 University of Delaware: Vehicle to Grid Demonstration Project (US)[63]

The University of Delaware had a two-year project that consisted of several research and development efforts from October 2008 to December 2010. This project paved the way for practical use of VtG technology. The University developed three separate components for a grid integrated vehicle (GIV), an electric vehicle with built-in communication and control software to enable interaction with the grid. First, the Vehicle Smart Link, an intelligent on-board system, was invented to help communicate with the aggregation server, monitor vehicle systems, and control charging. Second, VtG-capable Electric Vehicle Supply Equipment was designed to provide the required control for GIV. Third, aggregator software was developed to manage the complexity inherent in an operational VtG system. The project had manufacturing partners, AutoPort, Inc. and AC Propulsion, which converted five vehicles to VtG-capable electric vehicles called eBoxes.

The project also included research to enhance understanding of the environment in which VtG would be applied. Driving patterns were analysed to help design GIV systems. In addition, a vehicle choice survey with a sample of 3 029 respondents was conducted to identify the potential of EV and GIV markets. The survey revealed differences in willingness to pay for range increments and charging time between one group more inclined to purchase gasoline vehicles and another more inclined to purchase an electric vehicle.

After this project, the University carried on this work and formed a partnership with NRG Energy to commercialize VtG technology in September 2011. The project "eV2g" expanded to a large-scale demonstration project, partnering with PJM Interconnection and BMW.[64] In February 2013, the project became an official participant in the PJM's frequency regulation market and had sold power services from a fleet of EVs to PJM.[65] Some 15 BMW all-electric Mini-E equipped with a bidirectional battery charger (each capable of 12 kW of power to the grid) and 3 eBoxes were connected to the grid and aggregated to deliver 100 kW to the PJM's market. In April 2013, the project became an official resource of PJM Interconnection and proved for the first time that VtG technology could sell electricity from EVs to the power grid.

2.2.2 BMW ChargeForward: PG&E Electric Vehicle Smart Charging Pilot (US)[66]

This project tested the capability of EV's demand response (DR) and did an approximately year-long qualitative research effort to look into the needs and motivators of EV drivers. The aim of the project was to demonstrate the technical feasibility and grid value of managed charging of EVs as a flexible and controllable grid resource. In the DR system, the Pacific Gas and Electric Company (PG&E) initiated a DR event to BMW via Olivine and then BMW controlled to provide 100 kW of capacity in the form of either Day-Ahead (notifications sent 24+ hours before the event) or Real-time (notifications sent 4 minutes prior to the event) energy. Olivine, a certified scheduling coordinator with the California Independent System Operator (CAISO), worked as the interface between PG&E and

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[63] Kempton, W., Gardner M., Hidrue, M., Kamilev, F., Kamboj, S., Lilley, J., McGee, R., Parsons, G., Pearre, N., and Trnka, K. (2010), 'Vehicle to Grid Demonstration Project'

[64] Markel et al. (2015), *op. cit.*, p.32. PJM Interconnection is a regional transmission organization (RTO) that coordinates the movement of wholesale electricity in all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia. (http://www.pjm.com/about-pjm/who-we-are.aspx)

[65] University of Delaware (2013, April 27), 'Powering Up,' *UDaily*

[66] BMW Group and Pacific Gas and Electric Company (2017), "BMW i Charge Forward: PG&E's Electric Vehicle Smart Charing Pilot."

BMW, utilizing the Olivine DER which was a complete distributed energy resource management platform to manage the demand response program aspects of the pilot.[67]

BMW combined BMW i3 vehicles (each vehicle has a maximum capacity of 6.6 kW per charge) and the BMW Group 2nd life battery storage system to fulfil their DR commitment of 100 kW. BMW's back-end automated aggregation system was effective in optimizing the contribution of the vehicle pool and the stationary 2nd life battery storage while prioritizing the participants' driving needs. BMW enrolled 96 BMW i3 drivers within the South Bay Area to participate in this pilot.[68] The participants were also PG&E's customers and approximately 60% of them were on a time-of-use (TOU) rate plan.

The BMW ChargeForward project dispatched 209 DR events with a total pf 19 500 kWh from July 2015 to December 2016. BMW was able to meet the performance requirements for 90% (189) of the events. On average, about 20% of the 100 kW required was provided by the vehicle pool and the rest by the 2nd life stationary battery system. The share of the vehicle pool increased significantly during events within "off-peak" TOU periods in 23:00 – 2:00. The participants in the TOU rate plan had an incentive to charge their vehicles during the period when electricity tariffs were lower. However, there was no significant difference in the share contributed by either the vehicle pool or the stationary battery system between Day-Ahead and Real-time Energy. Although all participants were allowed to opt out of each DR event at any time, the opt-out rate was low throughout the program. This suggests that participants were not negatively impacted by the program.

To deepen understanding of charging behaviour and charging flexibilities of customers, a series of surveys were also conducted from February to December 2016. The survey result showed that most participants cited the incentive as a key motivation for program enrolment. The program provided the participants with an upfront incentive of US$1 000 and an ongoing incentive for each day they did not opt out up to US$540. As to charging behaviour, the study found that participants preferred to charge at night because it was easier. The barrier to daytime charging and charging away from home was that drivers were concerned about the inconveniences of charging stations, such as availability and cost of charging stations, and the risk that vehicles fully charged were still connected. Also, the participants regarded it as a highly important feature of the program that they were able to keep some control of their vehicles like setting a time a vehicle was needed at a desired charge level.

This project entered a second phase in 2017 and continued in 2018. A vehicle pool of more than 250 vehicles were employed to evaluate the grid benefits of increasing charging flexibility and customer engagement strategies that incentivize drivers to allow more flexibility in charging behaviour.

2.2.2.1 The U.S. Department of Defence Plug-in Electric Vehicle – Vehicle to Grid Program at Los Angeles Air Force Base (US)[69]

The United States Department of Defence (DoD) conducted a Plug-in Electric Vehicle – Vehicle to Grid (PEV-VtG) demonstration at four sites from 2015 to 2017.[70] The primary objective of this program

[67] Only a certified scheduling coordinator can directly bid resources as well as handle the settlement process in the CAISO market.

[68] 92 customers remained by the end of the polit. Only four customers left the project due to different reasons.

[69] Brendlinger, J., Campbell, M., Hlivko, J., Kaltenhauser, H., Wechtenhiser,B., and Hafer, G. (2017), 'Environmental Quality, Energy, and Power Technology. Task Order 0012: Plug-In Electric Vehicle, Vehicle-to-Grid'; California Public Utilities Commission, 'Southern California Edison Company's Department of Defense Vehicle-to-Grid Final Report'

[70] The four sites were (i) Los Angeles Air Force Base, California, (ii) Joint Base (JB) Andrews, Maryland, (iii) Fort Hood, Texas, (ix) JB McGuire-Dix-Lakehurst, New Jersey.

was to utilize VtG technologies with the idea that VtG technologies would provide financial and operational incentives to use plug-in electric vehicles as an energy resource beyond their basic function as a mobility asset. One of the four selected sites was Los Angeles Air Force Base (LAAFB) because it had a small, diverse general-purpose fleet of approximately 40 vehicles including 2-ton trucks and a shuttle bus as well as vehicles, and it was located in area where CAISO managed a frequency regulation market.

Before this project, the DOD launched the PEV-VtG program in 2011 and started collaborating with Southern California Edison Company (SCE). SCE assisted LAAFB to prepare participating in the CAISO market and was an approved scheduling coordinator with the CAISO. Lawrence Berkeley National Laboratory (LBNL) and Kisensum were contracted to design, develop and implement the software control systems to manage the EV fleet and to perform VtG activities at LAAFB.

LAAFB participated in CAISO's two types of day-ahead ancillary services market, regulation up (vehicle discharge) and regulation down (vehicle charge). LAAFB conducted a fully automated VtG demonstration in two phases: (i) with both regulation up and regulation down market participation from December 18, 2015, through January 26, 2017, and (ii) regulation up only from January 27, 2017, through September 30, 2017. LAAFB was permitted to participate in the regulation up market only for the second phase because CAISO decertified the VtG demonstration as a regulation down asset because of technical difficulty.[71] As a result, LAAFB received revenue US$7 639 in total by providing ancillary services from December 2015 through September 2017. For the cost aspect, LAAFB was charged monthly fees including a scheduling coordinator fee of US$1 000, a manual billing fee of US$118.46, and a meter data feed fee of US$216.50. On balance, the costs outweighed the revenues associated with market participation.

The PEV-VtG project successfully demonstrated that it was possible for PEVs to participate in an ancillary service market and yield revenues from market participation utilizing VtG technologies. The PEV battery worked as a distribution resource to help stabilize the power grid. However, the project also showed financial and technical issues to be solved for commercializing the PEV- VtG. The VtG operation did not make economic sense under current market conditions due to high infrastructure and equipment costs. The PEV-VtG project was not large enough to offset the costs and monthly fees, which were higher than the revenues realized by participating in the ancillary service market. Hence, economies of scale need to be considered for VtG deployment to be justified on commercial basis. Although this demonstration project proved the feasibility of VtG, it suffered from technical challenges as the VtG fleet of LAAFB was decertified for the regulation down market in the middle of the project. The report of this project estimates that the technology for VtG operation is several years away from being fully commercialized.

2.2.3 JUMPSmartMaui (Japan and US)[72]

New Energy and Industrial Technology Development Organization (NEDO) of Japan led the Japan – U.S. Collaborative Smart Grid Demonstration Project in Maui Island of Hawaii from 2011 to 2016. This so-called JUMPSmartMaui project was conducted in two phases, Phase 1 (October 2011 – March 2015) and Phase 2 (April 2015 – February 2017), and consisted of mainly three subjects, which were EV management, measures on distribution substations, and measures on low voltage grids.

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[71] According to CAISO, the V2G fleet failed to accurately respond to the regulation down automatic generation control (AGC) signal a minimum of 25% of the time during July and August 2016. (Brendlinger et al., p.15)

[72] New Energy and Industrial Technology Development Organization (NEDO)(2017), 'Japan-U.S. Collaborative Smart Grid Demonstration Project in Maui Island of Hawaii State: A case study,' NEDO Smart Community Case Study

Under the EV management initiative, three demonstration projects were operated: (i) EV Fast Charging Station Program in Phase 1 (387 participants), (ii) EV Charging Management Program in Phase 1 (190 participants), and (iii) VtG Program in Phase 2 (80 participants).[73]

The first EV Fast Charging Station Program started in September 2013 with installation of DC fast chargers at five charging stations in publicly accessible places such as shopping malls to help EV drivers utilize it and eventually expanded to 13 fast charging stations by the end of the program. When they registered, applicants obtained a smart card that allowed their EVs to be charged free at these designated charging stations, but program participants were charged monthly subscription fee of US$15 (US$30 for non-participants) for access to the fast charging stations after January 2015. Nevertheless, the number of vehicles using the fast charging stations gradually increased and reached 120 to 140 times per day on average after March 2015.

Second, the EV Charging Management Program aimed to assess the potential of controlling EV charging. The Integrated Distribution Management System (DMS), which was constructed to manage operation of the smart community project overall, worked to control EV charging to balance electricity demand and supply. The Integrated DMS was programmed to send a signal to each vehicle when charging should start based on data including estimated power generation from renewables and load the next day, connection status of EVs, and the time the participants expect their EVs to finish charging. The project was implemented in a way that the EVs were fully charged and ready by the time the participants needed them. Since there was no financial incentive attached to this program, the participants were expected to enrol on a voluntary basis. After launch of this program, the time EVs were most charged shifted from 19:00 – 20:00 to 22:00 – 23:00. This result shows that the charging management system could help alleviate peak load.

Third, the VtG Program was conducted to test whether discharging from EVs would support the stability of the power grid. Similar to the Charging Management Program above, the Integrated DMS was used to control the time to discharge from EVs. The participants were required to install a hardware EV-PCS at residence or office which enabled EVs to discharge electricity without financial incentives offered. Figure 2-2 illustrates that the VtG worked as intended. The EV charging was more levelled out and charging time shifted from peak demand hours (18:00 – 21:00) to midnight after the VtG program started. Furthermore, some vehicles discharged during the peak period to supply electricity as orange bars show in the figure.[74]

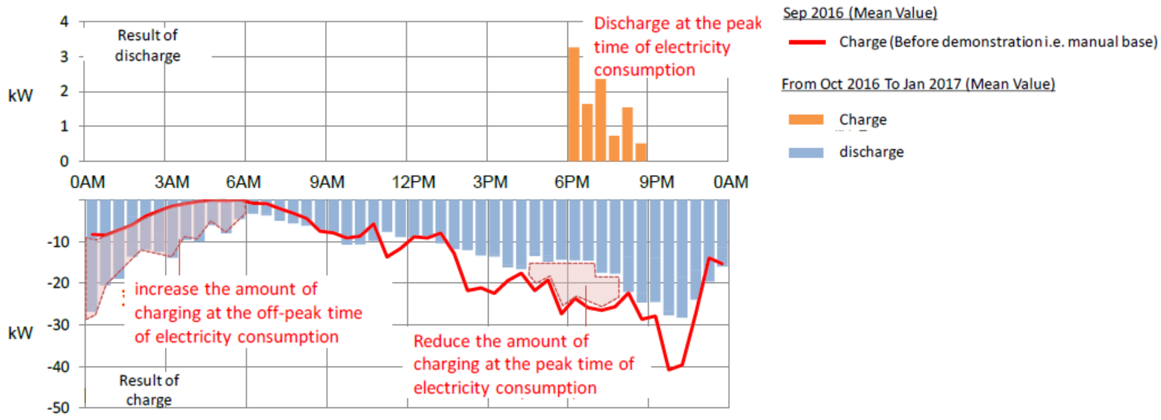
JUMPSmartMaui project was successful in gaining cooperation of the public. The project highlighted the importance of facilitating understanding about the project and building trust in community. The three demonstration projects did not provide the participants with financial incentives except for the period when charging was free at EV charging stations from September 2013 to January 2015. Yet, these projects attracted many voluntary participants as a result of the following factors. First, the project utilized various public relations. In addition to TV, radio, newspaper, and SNS, a flyer and website were prepared in a friendly way so that volunteers could better understand about the project without technical terms or jargon. Second, the project appealed to the public directly in several events, which were consequently effective at making the project visible and drawing attention. Third, the Maui Economic Development Board (MEDB), a local non-governmental organization, was helpful in bridging the gap in understanding or communication with people who were interested in participating and provided assistance at an individual level. Fourth, the project had support from the Mayor of

[73] Participation in multiple programs was allowed.

[74] Following the electric company's rules on grid connection, discharge was limited to 1 kW or less although EV-PCS can discharge up to 6 kW per unit, and the time for discharge was allowed within 30 minutes per event during 6 pm – 9 pm.

Maui County who was actively involved in the demonstration. The number of registered EVs on Maui Island increased from 68 in January 2011 to 800 in March 2017.

FIGURE 2-2. RESULT OF THE VTG PROGRAM



Note: IEEJ revised the legend of orange and blue bars to be correct at the bottom of the figure.

Source: NEDO (2017), p.9

2.2.4 Implications of the case studies

Overall, the demonstration projects indicate that VtG may be useful to control electricity demand and provide ancillary service if it is managed properly. There are several factors that could affect the commercial viability of VtG. First, technology needs to be advanced to a higher level to make the VtG system work effectively and smoothly. The success of VtG application is largely dependent on relevant technology development of the VtG system from the batteries to the operation systems. Technology innovation is also necessary for cost reductions.

Second, how large the VtG network can be extended at scale remains unclear. The projects referred to in this chapter were carried out in a relatively small scale with a limited number of participants. This suggests that VtG can be applied to a microgrid, but it is uncertain if it were to scale to a regional grid. Furtherer research and pilot projects on the VtG at a larger scale need to be pursued. If the VtG network is extended at a large scale, a long-term perspective is needed, because the necessary infrastructure and operation system development takes considerable time and investment.

Third, the VtG project design needs to be individually tailored to a targeted area. One VtG program of a specific area cannot be directly applied to another because of differences in electricity demand/supply structures and regional characteristics such as economy and population, even if the original program was considered a successful case. Hence, VtG systems require some adjustments to make them work for a focused area.

Fourth, how much cooperation the VtG project receives from participants makes a difference in the VtG operation. Financial incentives certainly affect participants' willingness to cooperate with the program. It is also crucial to raise the public awareness and facilitate understanding about the program, for instance, how the VtG works and what benefits the local area and participants will gain. Indeed, many people joined JUMPSmartMaui program even without financial incentives, since the various modes of public relations helped the residents to understand better that the program will reduce oil import dependence and consequently lower fuel costs and electricity tariffs.

Lastly, the VtG application entails new opportunities for business. For instance, aggregator service has established a new business model and is positioned as essential since demand response becomes more important to balance power supply and demand as a result of expansion of intermittent renewable energy use. There may be more ways to utilize EVs in the VtG system that cannot be accomplished with present available technology. Technology innovation may provide room for new business.

2.3 Cost/benefit of BEV and VtG/VtH to the consumer

The demonstration projects suggested that there are various challenges and expected benefits of associated with VtG.

BEV-grid integration centres on two issues: (i) how the BEV charging will affect the grid load, and (ii) how the energy storage capacity provided by BEV could be used for grid service.

The physical impact of BEVs on the grid is influenced by various factors. One is the uncertainty associated with the usage of BEVs and charging behaviour. Different driving and charging patterns translate into different time and duration of BEV charging. For example, if the main usage of a BEV is for commuting, the returning home time usually overlaps with the peak electric demand period, and if the customer starts charging as soon as arrival at home, BEV charging will dramatically increase the household's peak demand. However, if a BEV's charging time is moved to an off-peak time (for example, around midnight), the extra pressure on original peak demand can be avoided. The results from the "JUMPSmartMaui" demonstration project showed that the BEV owner's charging time can be managed in some way and the charging management system could help alleviate peak load.

Given the possible benefit of VtG, as found in the demonstration projects, to commercialize VtG in a large scale, several challenges still exist. Unlike stationary batteries, when and where BEVs would be connected to the grid is constrained by the usage of a BEV, the customer's charging behaviour, the availability EVSE, and so forth. Besides, the minimum capacity requirement for some grid services (such as frequency regulation) is much more than one individual BEV could provide. For BEVs to provide the same grid service as stationary batteries, the number of BEVs adopted needs to reach a certain level. That is, the pool of BEV needs to be large enough to ensure that a certain number of BEVs connect to the grid during the same period of time so that the BEVs can be aggregated to meet the requirement of certain grid services. Therefore, at the early stage of BEV adoption, VtG application is expected to be limited.

Another type of vehicle-grid integration is Vehicle-to-Home (VtH), or Vehicle-to-Building (VtB). Although not fully back to the grid, energy stored in a BEV's battery can also be used to power the electricity load of a household (VtH) or a building (VtB). Because VtH/VtB synchronization to the grid or a complex business model is not necessary, the control process and implementation are easier than VtG. Furthermore, VtH can be applied at the early stage of BEV adoption since the energy stored in an individual BEV is usually enough to power the household electricity demand.

VtH is especially attractive when the household is on a time-of-use tariff. By using a BEV to power household electricity demand during peak hours when the tariff is high and charging a BEV during off-peak hours when the tariff is low, the electricity bill for the household is expected to be reduced. VtH could also provide backup power in an emergency when the electricity supply from grid is cut off.

In the following part of this section, a case study is carried out to quantitatively evaluate the economic cost/benefit of BEV and VtH to the consumer. The study chooses Japan as an example for the case study. Although the case of Japan could not represent all the situations in the APEC economies, Japan is in the frontline of VtH demonstrations in the APEC region and associated data needed for the simulation is also available for Japan.

2.3.1 Preconditions and scenarios for the simulation

Based on the driving cycle, charging behaviour, charging/discharging conditions (in case of VtH), BEV and EVSE technology specifications, and BEV hourly charging profile for a full year is calculated.

Evaluation of BEV and VtH economic impact requires an electricity tariff. In this study two types of electricity tariff for residential customers, and one type of electricity tariff for commercial customers are assumed, based on Tokyo Electric Power Company's electricity tariff plan.

2.3.1.1 Assumptions on driving cycle

A vehicle's driving cycle depends on the main use of the car, e.g. private or business use, and a driver's lifestyle (if for private use). Driving distance is also influenced by population density. Rather than include all possibilities, this study focuses on patterns of a typical private BEV.

According to the Origin/Destination Survey[75] (2005) data compiled in Satoshi Nakaue (2010),[76] in Japan the most common usage of a private LDV is for commuting during workdays and errands during weekends. The distance of most commuting trips is less than 15 km and less than 10 km for errands. The same study also shows that the distribution for leaving home time and returning home time for commuters peaks around 7:00 – 8:00 and 17:00 – 18:00 respectively. Leaving home time for weekday errands shows relatively flat distribution over 10:00 – 19:00, while the leaving home time for weekend errands has two peaks: 10:00 – 11:00, and 14:00 – 15:00. Based on the above findings, three driving itinerary patterns are assumed (Table 2-2) for the case study. Pattern 1 is weekday commute and weekend errands, the most common pattern of vehicle use. Pattern 2 and 3 are based on BEV use for errands both on weekdays and weekends, while pattern 2 assumes two errand trips on weekends and pattern 3 assumes BEV use in the evening on weekdays.

TABLE 2-2. ASSUMPTIONS FOR DRIVING ITINERARY IN JAPAN

	Pattern 1		Pattern 2		Pattern 3	
	W/day	W/end	W/day	W/end	W/day	W/end
Distance per trip, km	15	10	10	10	10	10
Trips per day	2	2	2	3	2	2
Driving speed, km/h	50	50	50	50	50	50
Trip 1 starting time	8:00	11:00	10:00	11:00	18:00	11:00
Trip 2 starting time	-	-	-	14:00	-	-
Return trip starting time	17:00	15:00	14:00	16:00	19:00	15:00

Source: assumed by authors based on Origin/Destination Survey (2005) data compiled in Nakaue, S. (2010)

Note: W/day = weekday, W/end = weekend.

2.3.1.2 Technology spec for BEV and EVSE

According to the IEA, most commonly battery the capacity for BEVs range of 20 - 60 kWh.[77] The simulation assumes that the BEV battery capacity is 30 kWh. The assumption on the BEV electricity consumption is also in line with the same IEA study, which is 0.2 kWh/km.

Three types of EVSE are used in the simulation: home EVSE (level 1) with a power level of 3 kW; workplace EVSE (level 2) with a power level of 7 kW; and fast charging EVSE (level 3) with a power level of 20 kW.

2.3.1.3 Charging pattern

This study assumes that home charging is available for all cases. And to examine the impact of workplace charging, two cases, in which workplace charging is available and not-available are assumed. Charging at public or commercial facilities like a shopping centre or a sports gym is not

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[75] Japan Ministry of Land, Infrastructure, Transport and Tourism (2005), Origin/Destination Survey

[76] Nakaue, S. (2010), 'Evaluation of penetration of Plug-in Hybrid Vehicles and Electric Vehicles considering optimal power generation mix', Master thesis paper, pp.9-23.

[77] IEA (2018), Global EV Outlook 2018 Towards cross-modal electrification, Paris: OECD/IEA

assumed. This study also assumes that fast charging stations are available. However, the condition for using fast charging is that home charging and workplace charging are not available when the SOC level (State of Charge, which is the ratio of the battery's remaining energy against the capacity of the battery (measured by kWh)) of the BEV battery is low.

An important factor determining the BEV's charging curve is under what condition BEV charging will be triggered. Consumer tolerance on SOC level before charging is affected by various factors. A study of NISSAN LEAF driving and charging behaviour undertaken by the Idaho National Laboratory and Ecotality found that in most cases the SOC level before home charging was 30% - 60%, and for charging away from home 40% - 70%.[78] Since a higher SOC level before BEV charging would result to more frequent BEV charging and the impact of BEVs and VtH easier to identify, this study assumes higher SOC levels before charging: 90% for home charging, 95% for workplace charging, and 50% for fast charging. Although various SOC levels before charging will result in quite different charging profiles, in this simulation the details of the correlation between the SOC level and consumers' charging behaviour will not be discussed.

2.3.1.4 Vehicle-to-home (VtH)

As mentioned above, vehicle to home is likely to be the most practical form of vehicle grid integration in the near term. In reality, the operation of a VtH system involves various factors such as the BEV battery SOC level, tariff level, household load, etc. In this study a simplified control process is assumed: electricity flows from a BEV to power home electric load when the vehicle is parked at home and the SOC is above 20% the BEV will supply the household's electricity demand as long as the SOC is higher than 20%; when the SOC is lower than 20% the BEV will stop discharging and begin charging till it reaches 100% SOC.

TABLE 2-3. ASSUMPTIONS ON ELECTRICITY TARIFF

Tariff type		Rate
Residential flat rate	Flat tariff rate	JPY28.5/kWh (US$0.25/kWh)
Residential TOU	Day-time (8:00 - 22:00)	JPY32/kWh (US$0.29/kWh)
	Mid-night (23:00 - 7:00)	JPY20/kWh (US$0.18/kWh)
Commercial	Jul - Sep	JPY17.22/kWh (US$0.15/kWh)
	Other	JPY16.08/kWh (US$0.14/kWh)
Fast charging		JPY18/kWh (US$0.16/kWh)

Note: Adapted from TEPCO tariff plan[79] and fast charging rate[80] in term of time; Exchange rate 1US$=112JPY (IMF (2018))

Source: TEPCO and estimation by authors based on fast charging rate

2.3.1.5 Electricity tariff

To assess the economic impact of the BEV assumptions on electricity a tariff rate is necessary. Two types of residential electricity tariff, and one type of commercial electricity tariff are applied in the simulation (Table 2-3). The tariff assumptions are based on Tokyo Electric Power Company's (TEPCO) tariff schedule. The tariff rate for fast charging is based on usage over a certain time (JPY15/min).

[78] Smart, J. and Schey, S. (2012), 'Battery Electric Vehicle Driving and Charging Behavior Observed Early in The EV Project', https://avt.inl.gov/sites/default/files/pdf/EVProj/NissanLeafDrivingChargingSlides.pdf

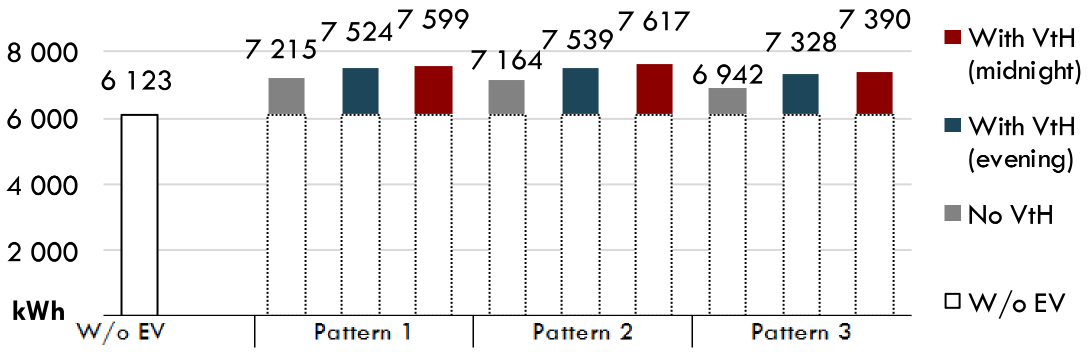
[79] Tokyo Electric Power Company (TEPCO), http://www.tepco.co.jp/ep/private/plan/

[80] Nippon Charge Service LLC, https://www.nippon-juden.co.jp/tk/cd/

2.3.2 Economic Impact of BEV and VtH

For the simulation cases, BEV charging results in 819 - 1 494 kWh annual electricity demand increase depending on driving pattern and whether VtH is enabled (Figure 2-3). If there is no VtH, the additional annual electricity consumption caused by BEV is almost the same regardless of the charging pattern. However, enabling VtH will result to more charging/discharging cycles of the BEV battery and thus more electricity lose during the cycles and more annual total electricity consumption of the household.

FIGURE 2-3. ANNUAL ELECTRICITY CONSUMPTION WITH BEV/VTH

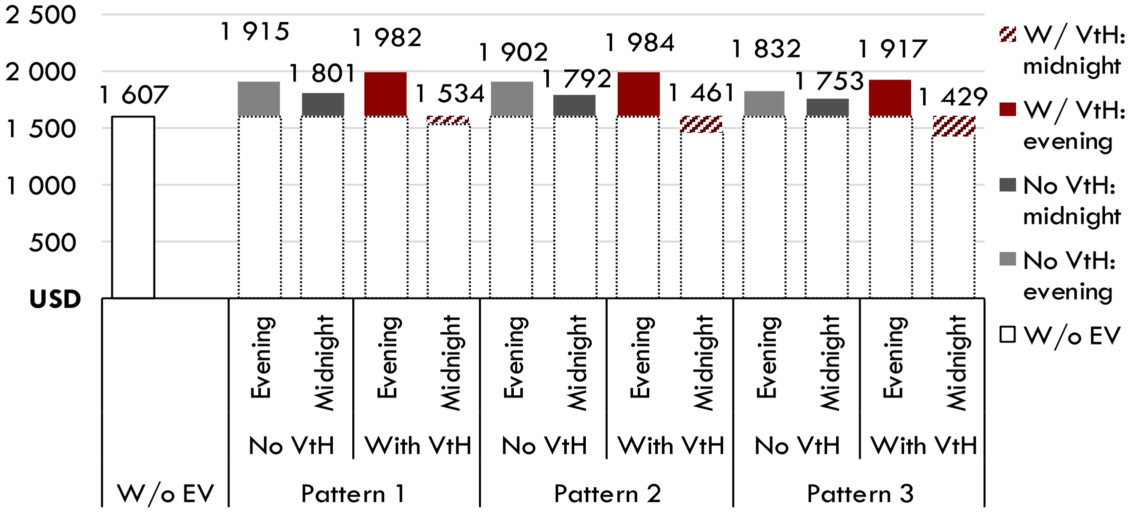


Source: The Institute of Energy Economics, Japan

2.3.2.1 Economic impact of BEV charging and VtH under different tariff schedule

Since BEV charging will result in additional electricity consumption for the household, if the consumer is subject to flat tariff rate, the annual additional expense for electricity caused by a BEV is around US$208 - 380. Under this tariff type, because the additional cost difference is so small, the consumer has no incentive to charge the BEV during the off-peak time rather than choosing to charge the BEV as soon as arriving home. Besides, since VtH will result in more electricity consumption, and more expense on electricity, VtH is not economically attractive to consumers under a universal tariff.

FIGURE 2-4. ANNUAL EXPENSE OF BEV CHARGING UNDER TOU TARIFF (WITH AND WITHOUT VTH)



Source: The Institute of Energy Economics, Japan

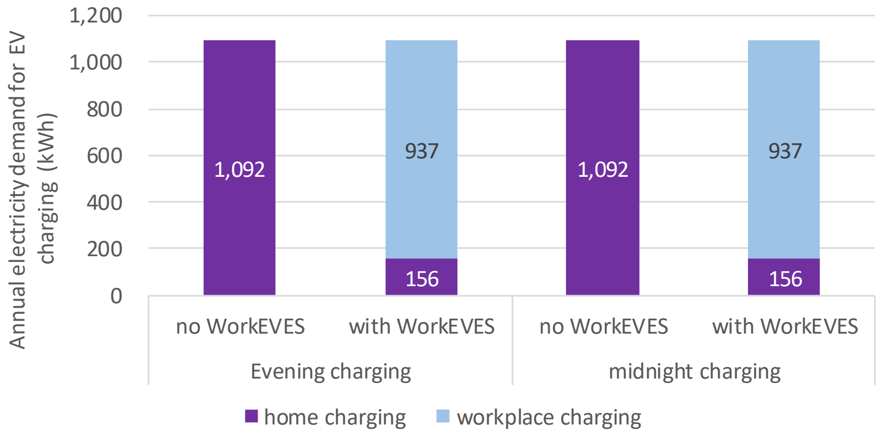
However, under the time-of-use (TOU) tariff, where the tariff rate is higher during peak-hours and lower during off-peak hours, variation in BEV charging time will result in a different economic impact. If the consumer chooses to charge the BEV during off-peak midnight time, when the tariff is cheaper, the additional expense caused by BEV charging is less than charging the BEV when plugged in when returning home (Figure 2-4).

Furthermore, under the TOU tariff, if the consumer enables VtH, using the BEV to power the household when the tariff is high and charging the BEV when the tariff is low, the consumer's annual expense for electricity is actually lower than that without BEV and VtH (Figure 2-4). This means under the TOU tariff, the BEV helps consumers reduce their bills.

2.3.2.2 Impact of workplace charging

Under the charging condition assumptions of the study, if EVSE is available at the workplace, most of BEV charging will happen at workplace (Figure 2-5).

FIGURE 2-5. ANNUAL BEV CHARGING ELECTRICITY CONSUMPTION W/O WORKPLACE CHARGING

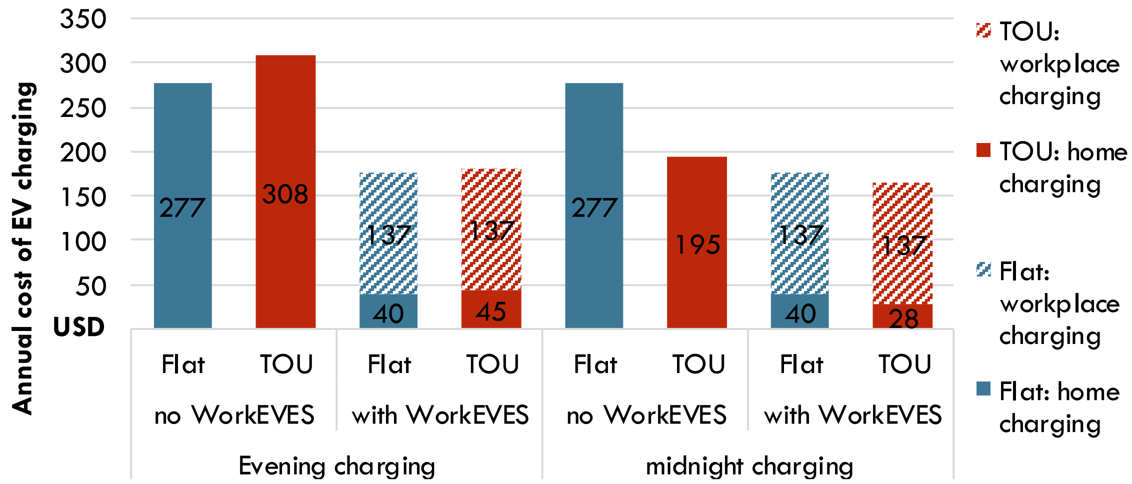


Note: no VtH

Source: The Institute of Energy Economics, Japan

Since the commercial electricity tariff is cheaper than that of the residential, compared with charging at home solely, charging the BEV at the workplace could help reducing the cost on BEV charging (Figure 2-6). If the residential tariff is flat, there is little cost difference between evening charging and midnight charging. Under the TOU tariff, evening charging costs about US$126 more than midnight charging when there is no workplace charging and US$30 more when workplace charging is available. When workplace charging is available, most of the charging happens at the workplace thus, home charging behaviour has less economic impact.

FIGURE 2-6. ANNUAL COST ON BEV CHARGING (FLAT TARIFF)



Note: no VtH

Source: The Institute of Energy Economics, Japan

3 Study of impacts of FCEVs on electricity demand/supply

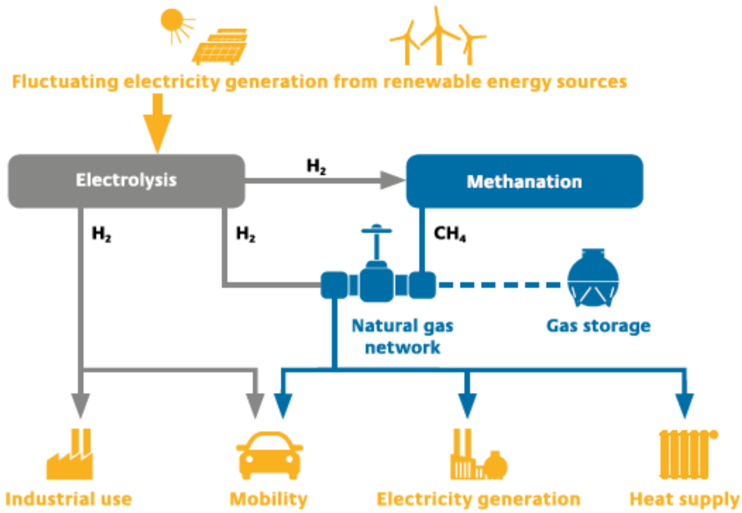
FCEVs are powered by hydrogen and considered as one option for low-carbon mobility. There are several ways to produce hydrogen. The most common technology is steam-methane reforming which uses a reaction of fossil fuels such as natural gas and coal, and high-temperature steam to generate hydrogen. However, the steam-methane reforming process is accompanied with CO_2 emissions, which makes hydrogen improper for a low carbon energy regime unless the facility is equipped with carbon capture and storage (CCS) technology. Instead, this chapter focuses on power-to-gas (PtG) as a means of producing CO_2-free hydrogen. First, a brief explanation on PtG is provided and the benefits and challenges of PtG follow. Then, some PtG demonstration projects are described to see recent technology development. The last part is a more detailed discussion on the grid impact and the economics of PtG.

3.1 Benefits and challenges of power-to-gas (PtG)

3.1.1 Overview of PtG

PtG transforms electricity from renewable energy sources such as solar and wind power into hydrogen via electrolysis (Figure 3-1). Hydrogen can be directly blended into existing natural gas pipelines although the acceptable concentration rate is limited, generally 1% - 20%. In a subsequent methanation process, synthetic methane (synthetic natural gas) is also produced by combining the hydrogen and CO_2. Hydrogen and synthetic methane are delivered for various energy uses such as in the industry and transport sectors. Hydrogen can be stored at fuelling stations in the form of compressed hydrogen or liquefied hydrogen.

FIGURE 3-1. CONCEPT OF POWER-TO-GAS



Source: DENA (2015)[81]

In PtG, electrolysis and methanation are the key technologies. Electrolysis is "a process of splitting water into hydrogen and oxygen by applying a direct current, converting electricity into chemical energy."[82] There are three types of electrolysers: alkaline electrolyser, PEM (proton exchange membrane) electrolyser, and solid oxide electrolyser. Alkaline electrolysers are the most mature, the least cost, the longest life, and more efficient technology compared with the other two (Table 3-1).

[81] German Energy Agency (DENA)(2015), 'Power to Gas system solution, Opportunities, Challenges and Parameters on the Way to Marketability,' p.5

[82] IEA (2015), Technology Roadmap – Hydrogen and Fuel Cells, Paris: OECD/IEA

On the other hand, PEM electrolysis has several advantages over alkaline electrolysis although it is relatively new and available only on a small scale. For instance, PEM electrolysis can be more flexible in that the range of PEM electrolysis is 0% - 160% nominal load whereas that of alkaline electrolysis is 15% - 100% nominal load.[83] Furthermore, PEM electrolysis is more reactive with a rapid start-up time of 1 second – 5 minutes, whereas alkaline electrolysis needs a longer start-up time of 1 - 10 minutes. With higher power densities, PEM electrolysers require less space compared with alkaline electrolysers.[84] Solid oxide electrolysis is still in R&D phase but could be a game changer in the medium term.[85] PEM and solid oxide electrolysis are expected to have potential for efficiency improvements and cost reductions.

TABLE 3-1. COMPARISON OF DIFFERENT ELECTROLYSER TECHNOLOGIES

Electrolyser	Capacity, kW	Efficiency	Initial investment cost, US$/kW	Life time, hour	Maturity
Alkaline	≤ 150	65-82% (HHV)	850 - 1 500	60 000 - 90 000	Mature
PEM	≤ 150 (stacks) ≤ 1 000 (systems)	65-78% (HHV)	1 500 - 3 800	20 000 - 60 000	Early market
Solid Oxide	Lab scale	85-90% (HHV)	-	~1 000	R&D

Note: HHV = higher heating value

Source: IEA (2015), p.28

A further conversion process in PtG is methanation, that is, "a chemical reaction that converts carbon monoxide and/or carbon dioxide to methane."[86] The "Sabatier" reaction, a well-known chemical process for combining hydrogen and CO_2, is used to form synthetic methane. The Audi e-gas project utilizing this methanation process will be described later.

3.1.2 Expected benefits of power-to-gas

3.1.2.1 Decarbonisation of the end-use sectors

PtG is expected to contribute to decarbonisation of the end-use sectors. PtG has provided alternative fuels, hydrogen and synthetic methane, to the transport sector which heavily relies on fossil fuels. In road transport, FCEVs have proved to lower CO_2 emissions compared with internal combustion engine vehicles (ICEVs). Even if hydrogen were produced from natural gas via steam methane reforming without the use of carbon capture, CO_2 emissions of FCEVs are 20% - 30% lower than those of ICEVs.[87]

In addition to passenger vehicles, where FCEV is currently commercially available, heavy-duty vehicles may be made marketable as fuel cell trucks and buses, since FCEV has advantages over EV for heavier vehicles travelling longer distances.[88] In China, as of May 2018, there were 150 fuel cell

[83] International Renewable Energy Agency (IRENA) (2018), *Hydrogen from Renewable Power – Technology Outlook for the Energy Transition*, Abu Dhabi: IRENA, 2018, p.23

[84] Dragoon, Ken (2018), 'Power to Gas – Opportunities for Greening the Natural Gas System,' Flink Energy Consulting Study Commissioned by NW Natural

[85] IRENA (2018), *et. al.*, p. 23

[86] HELMETH, 'Methanation process,' http://www.helmeth.eu/index.php/technologies/methanation-process

[87] Hydrogen Council (2017), Hydrogen Scaling Up – A Sustainable Pathway for the Global Energy Transition, pp.35-36

[88] IRENA (2018), *op. cit.*, pp.33-34.

buses; 500 fuel cell trucks started operation for intra-city delivery of goods in Shanghai in January 2018.[89] Europe, Japan, and Korea are also keen to deploy more fuel cell buses.

In the longer term, decarbonisation of the transport sector is likely to be seen in rail transport, shipping and aviation as well. In September 2018, the world's first hydrogen fuel cell train entered commercial service, running on nearly a 100 km route between the towns and cities of Lower Saxony, Germany.[90] Hydrogen used in this train is fossil fuel-based but this operation helps eliminate pollutant emissions related to propulsion and demonstrates the practicality of fuel cell trains.

As with the transport sector, hydrogen from renewable energies provides a substantial potential for greenhouse gas emission reductions in the industry sector. Hydrogen has been long used in several industry sectors, mainly in the chemical, refining and steel industries.[91] However, currently, more than 95% of hydrogen production is fossil fuel-based by means of steam methane reforming in most cases and oil and coal gasification to a lesser extent.[92] Therefore, hydrogen produced from renewable energy as a carbon-free energy carrier needs to replace fossil fuel-based hydrogen to decarbonize the industry sector. For this purpose, the cost of low-carbon hydrogen needs to be reduced to be competitive with fossil fuel-based hydrogen.

Lastly, with the use of the existing natural gas infrastructure, hydrogen and synthetic methane from the PtG process can be delivered to the residential and commercial sectors as the heating fuel. Even though addition of these gases from the PtG process into natural gas pipelines is limited, this substitution will result in reduction of conventional natural gas use in heating.

3.1.2.2 Integration of variable renewable energy into the electricity system

An equally important benefit that PtG will bring is to reduce curtailment of renewable energy generation. Generation and consumption of electricity must always be balanced but power supply from fluctuating renewable energies could cause an imbalance in the electricity system if power supply is more than power demand. While the expectation for renewable energy such as solar and wind to reduce CO_2 emissions is increasing, the variable nature of these energy sources poses a serious challenge: that is, how to balance with concurrent demand when solar and wind are oversupplied or not sufficiently available.

PtG helps integrate significant quantities of variable renewable energy into the energy system. In the PtG process, electrolysers can be adjusted to the fluctuation of solar and wind power generation, which works to absorb excess electricity. Thus, instead of curtailment, surplus power supply from renewable energies can be stored after transformation to hydrogen or methane. Furthermore, the PtG process can contribute to frequency regulation services because of its flexibility.

As Figure 3-2 shows, Germany faces an issue of increasing curtailment of electricity as installed capacity of wind and solar power increases. In other words, it is urgently necessary for Germany to control and absorb variable renewable energy since the economy plans to increase its share of renewable energy in gross electricity consumption to 40% - 45 % by 2025, 55% - 60% by 2035, and 80% by 2050.[93] Under such circumstances, Germany globally leads demonstration projects in

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89 IPHE, 'IPHE Country Update: May 2018 – China'

90 Alstom (2018, September 16), 'World premiere: Alstom's hydrogen trains enter passenger service in Lower Saxony'

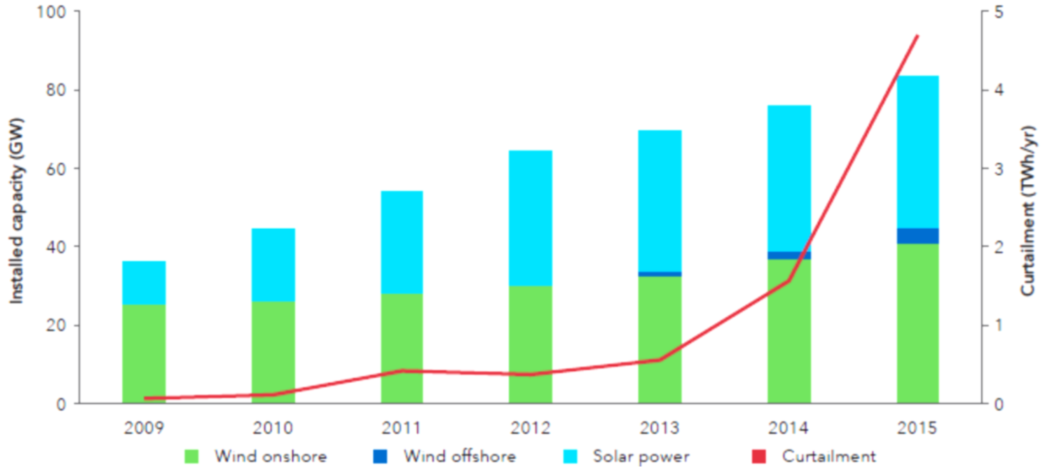
91 Hydrogen is used as feedstock in the refining industry for hydro-treating and hydro-cracking, and the chemical industry for production of ammonia and polymers. In the steel industry, by-product hydrogen during the coke, iron and steelmaking processes is used for site thermal requirements.

92 IRENA (2018), *op. cit.*

93 German Federal Ministry of Economic Affairs and Energy (2014), Act on the Development of Renewable Energy Sources (Renewable Energy Sources Act - RES Act 2014), Part 1, Section1(2)

PtG. As of the first quarter of 2017, there were 70 PtG projects operating or planned in Europe, 40 of which were in Germany.[94]

FIGURE 3-2. INSTALLED CAPACITY OF WIND AND SOLAR POWER AND CURTAILMENT IN GERMANY

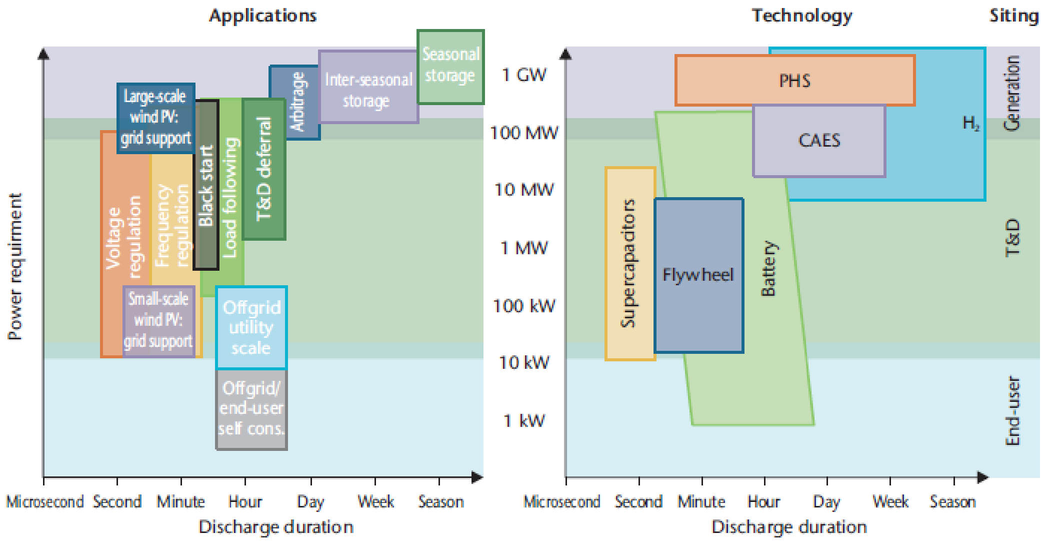


Source: European Power to Gas (2017), p.7

3.1.2.3 Large-scale and long-term energy storage

Hydrogen and methane are energy carriers that can be stored on a large scale at the time of production and for a long duration, from hours to seasons (Figure 3-3). Storing hydrogen as a compressed gas is more common than liquefaction, whose costs are higher. Leveraging the existing natural gas infrastructure for hydrogen storage would help to cope with changes in seasonal demand for electricity and heat as well as to reduce the necessity of expanding or building new gas infrastructure. Underground storage of town gas has a long history in Europe and could hold large volumes. This is one option for storage, depending on the geological formation and economic and technical feasibility.

FIGURE 3-3. ELECTRICITY STORAGE APPLICATIONS AND TECHNOLOGIES



Note: CAES = compressed air energy storage, PHS = pumped hydro energy storage

Source: IEA (2015), p.20

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[94] European Power to Gas (2017), 'Power-to-Gas in a Decarbonized European Energy System Based on Renewable Energy Source,' p.21

3.1.3 Challenges of power-to-gas

3.1.3.1 Infrastructure development

Infrastructure development such as electrolysers and transport systems for hydrogen and methane is a challenging task for PtG to be widely applied, although it is fundamental for the PtG process. Primarily, the PtG process necessitates a high level of investment because PtG facilities are capital intensive regardless of whether the existing natural gas infrastructure is utilized. In particular, electrolysers require substantial investment costs as previously demonstrated in Table 3-1. If low-cost renewable electricity is available and utilization rates of electrolysers are high, the PtG process could become cost-effective.

Logically, demand for hydrogen or synthetic natural gas needs to be increased or secured. Otherwise, infrastructure development will not be pursued. The economy of scale would not be economic without hydrogen demand increases. Currently, fossil fuel-based hydrogen is more inexpensive in the end-user sectors. In the transport sector, FCEVs are quite expensive even with a subsidy compared with average types of ICEs. A Toyota Mirai is available to purchase for a manufacturer's suggested retail price of US$58 365 plus an US$920 destination fee.[95] In addition, deployment of FCEVs needs to be accompanied by coordinated development of hydrogen fuelling stations, whose costs are much higher than gasoline stations. According to a report of the California Energy Commission and the California Air Resources Board, total installed costs, which include equipment, design, construction, and commissioning, were estimated to be slightly over US$2 million for a 180 kg/day delivered gaseous hydrogen refuelling station, US$2.8 million for a 350 kg/day delivered liquid hydrogen refuelling station, and US$3.2 million for a 120 kg/day produced on-site electrolysis hydrogen refuelling station.[96] Hence, cost reductions through technology advancement and economies of scale is a crucial condition for infrastructure development of PtG.

Dependence on the existing natural gas infrastructure indicates constraints in blending share of hydrogen. If hydrogen concentrations are relatively low, the existing natural gas infrastructure could be operated safely without additional infrastructure development. However, hydrogen could damage steel materials used for the pipelines if it exceeds a certain level. As demand for hydrogen increases, adequate infrastructure development to transport and store hydrogen is necessary in the long-term perspective.

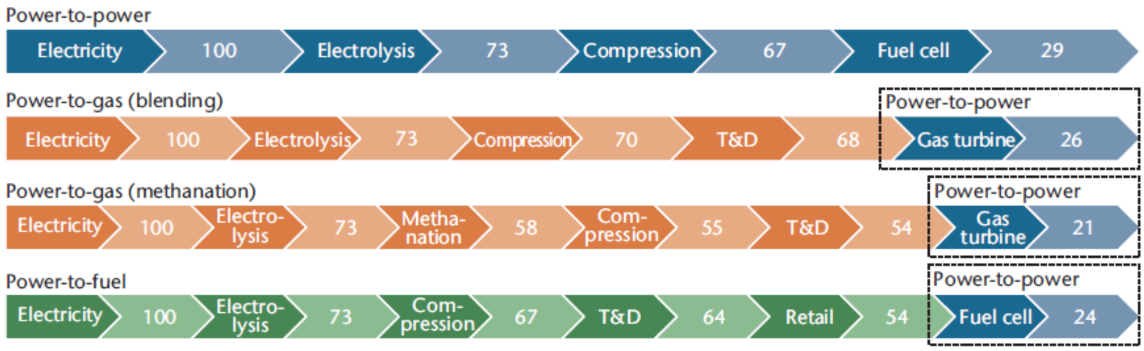
3.1.3.2 Technology advancement

Technology advancement is necessary to make PtG more affordable and available in the market, since most technologies used in the PtG process are not mature yet or expensive to apply. Most importantly, technology development of electrolysers is key to render cost reductions to the PtG procedure. Another issue in technology improvement of the PtG process is the low efficiencies in the conversion of renewable energies through electrolysis to a fuel cell or a hydrogen gas turbine (Figure 3-4). The efficiency diminishes to the range of 20% - 30% ultimately. The more processes the transformation goes through, the less efficient the PtG system is. For instance, the solid oxide electrolyser that is currently in the R&D phase could improve efficiency if a technology breakthrough makes it commercially usable.

[95] Toyota Motor Sales, U.S.A., Inc., https://ssl.toyota.com/mirai/faq.html

[96] California Energy Commission and California Air Resources Board (2015), 'Joint Agency Staff Report on Assembly Bill 8: Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California,' pp.38-50

FIGURE 3-4. CURRENT CONVERSION EFFICIENCIES OF VARIOUS HYDROGEN-BASED VRE INTEGRATION PATHWAYS



Note: The numbers denote useful energy; except for gas turbines, efficiencies are based on higher heating value; the conversion efficiency of gas turbines is based on lower heating value.

Source: IEA (2015), p.21

3.1.3.3 Regulatory framework

A policy and regulatory framework that will facilitate the PtG process needs to be established or revised if current regulations are barriers to deployment of the new technology. Given legitimate technical and economic conditions and credibility in the market, application of PtG technology and investment in the PtG process will be encouraged. A possible example is to set a stricter mandatory target of CO_2 emission reduction, which can be a major driver to utilize hydrogen produced from renewable energy. Taking one step further, a certification system like CertifHy in EU seems effective in facilitating hydrogen production from renewable energy.[97] Such a certification system would prove that electricity is generated from renewable energy and make green hydrogen a tradable asset, which would stimulate hydrogen demand from the end-users and help set the hydrogen price in the market.

3.2 Case study of PtG

3.2.1 Energie Park Mainz (Germany)[98]

The world's largest green hydrogen plant, "the Energy Park Mainz" (Figure 3-5), was developed by four partners; RheinMain University of Applied Sciences, Siemens AG (a global power equipment supplier), Linde AG (a world-leading gases and engineering company), and Mainzer Stadwerke AG (one of the leading municipal utilities). The project started in 2012 and has been in the commercial testing phase since 2017. The primary objective is the development, testing and application of innovative technologies for producing hydrogen via electrolysis powered by renewable energies. In order to optimize PtG plant operation, the energy park participates in a secondary control reserve market and purchases power on the spot market.[99]

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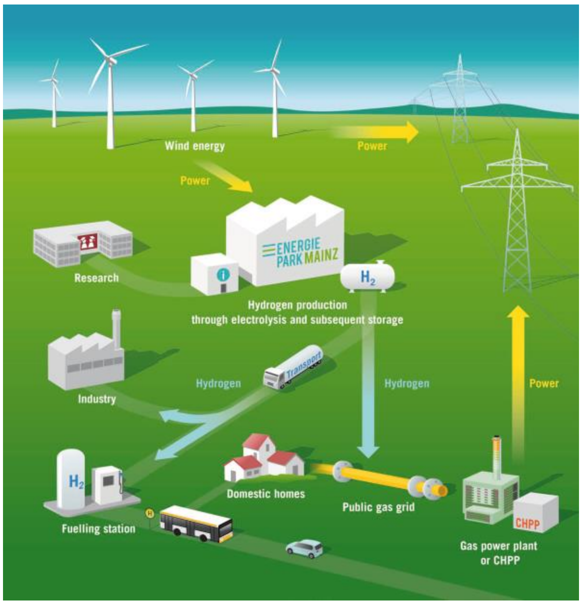
[97] CertifHy aims to develop the first European-wide green and low-carbon hydrogen guarantees of origin (GO) scheme.

[98] Energie Park Mainz, http://www.energiepark-mainz.de/en/

[99] In Germany, three hierarchical levels of load-frequency controls are conducted at primary, secondary and tertiary controls, which differ in response time and control characteristics. (Just, S. (2015), 'The German market for system reserve capacity and balancing energy,' EWL Working Paper, No. 06/15, University of Duisburg-Essen, Chair for Management Science and Energy Economics, p.6)

The PtG system is directly connected to the medium-voltage grid (20 kV) of Stadtwerke Mainz and linked to four adjacent wind parks (4 × 2 MW) of the Stadtwerke group. Three PEM electrolysers are operated, with a peak performance of 2 MW each. Since PEM-based systems are usually available at small scale, the operation of PEM electrolysers in this large scale shows revolutionary advancement of technology.

FIGURE 3-5. ENERGIE PARK MAINZ



Source: Energy Park Mainz (2018)[100]

The hydrogen produced in the energy park are utilized in two ways. One application is feeding into the natural gas grid of Stadtwerke Mainz with volume flow up to 1 000 m^3/hour. [101] Alternatively, the hydrogen is also put in trucks which they use a fully automatically process at hydrogen fuelling stations. Filling time is approximately three hours. In the future, hydrogen from the energy park will be tested in a steam turbine power plant of Kraftwerke Main-Wiesbaden AG (the municipal energy producer) at Ingelheimer Aue. This will be proof of a green power supply even when there is no wind.

3.2.2 Audi e-gas project (Germany)[102]

Audi started to operate the world's first industrial-scale PtG plant in Werlte, northern Germany, in 2013 (Figure 3-6). Excess wind power is mainly used in electrolysers (3 × 2MW) to split water into oxygen and hydrogen. Then, hydrogen is combined with CO_2 from a biogas plant in the methanization facility to generate synthetic natural gas (synthetic methane), so-called Audi e-gas, which is available to owners of Audi CNG passenger vehicles. The plant produces 1 000 tonnes of methane per year. This synthetic natural gas can be fed directly into natural gas pipelines or stored. In addition, this PtG facility was qualified to participate in the electricity balancing market in 2015, which is expected to contribute toward stabilizing the public power grid.[103] Audi estimated well-to-wheels CO_2 emissions of vehicles with different fuels. In the case of compact class with mileage of 200 000 km, they found that CO_2 emissions of Audi e-gas produced from wind energy were reduced by 85% compared with fossil-generated natural gas.[104]

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[100] Energie Park Mainz (2018), "A spirit of innovation is in the air!", http://www.energiepark-mainz.de/fileadmin/user_upload/energiepark-mainz-brochure-2018.pdf

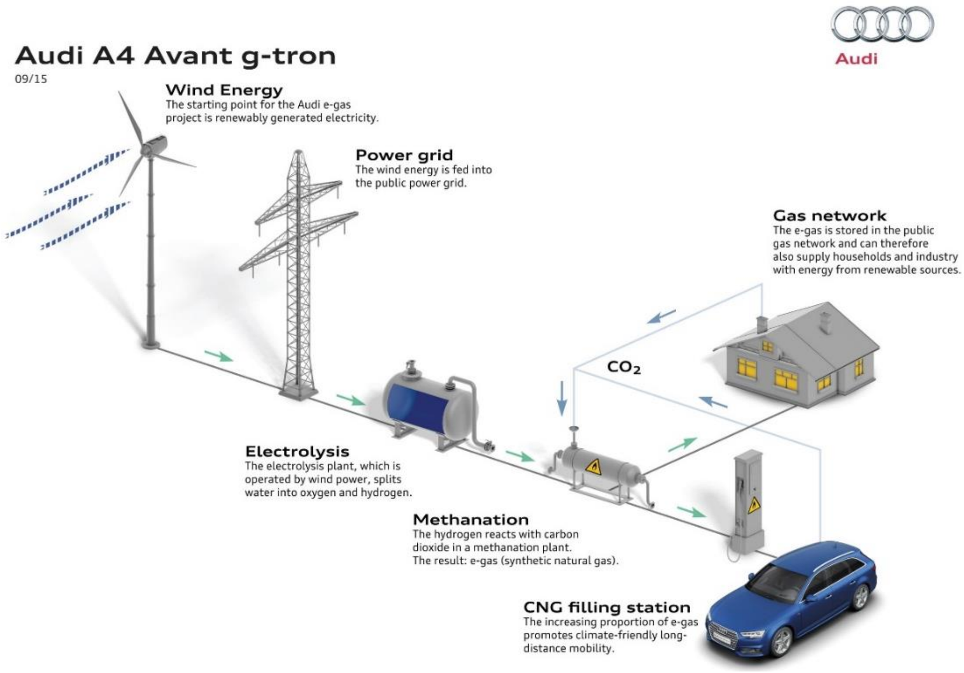
[101] Kopp, M., Stiller, C., Scheffer, K., Aichinger, J., and Scheppat, B. (2016, Mach 1), 'Power-to-Gas Project "Energiepark Mainz – Operational and economical analysis of the worldwide largest Power-to-Gas plant with PEM electrolysis,' presented at IEA Workshop Energy Storage in Germany – R&D for the Energy Systems Transformation, in Garching, Germany

[102] Audi, 'Audi e-gas,' https://www.audi-technology-portal.de/en/mobility-for-the-future/audi-future-lab-mobility_en/audi-future-energies_en/audi-e-gas_en

[103] Audi USA (2015, July 15), 'Audi e-gas plant helps stabilize German public power grid'

[104] Otten, R. (2014, May 27), 'The first industrial PtG plant – Audi e-gas as driver for the energy turnaround,' presented at CEDEC Gas Day 2014 in Verona, p.33

FIGURE 3-6. AUDI E-GAS PROJECT



Source: Audi[105]

3.3 Grid impact, and economics of FCEV and PtG

3.3.1 National Renewable Energy Laboratory and Southern California Gas Company (US)[106]

The National Renewable Energy Laboratory (NREL) and Southern California Gas Company (SoCalGas) have taken a novel approach to PtG. In 2017, NREL and SoCalGas installed a pilot scale bioreactor (approximately 7.6 m tall) outside NREL's Energy System Integration Facility in Colorado (Figure 3-7). This project manages up to 250 kW of varying power such as wind and solar, using an electrolyser to split water into hydrogen and oxygen. Then, the hydrogen is combined with CO_2 and fed into the bioreactor where methanogens produce methane and water. This process produced gas that will meet pipeline quality specifications with minor filtration and can be injected into the existing natural gas infrastructure. NREL and SoCalGas will assess the potential impact of this PtG approach on energy storage in terms of finance and operation. As NREL notes, this is a unique challenge that involves electricity, renewable based hydrogen production, anaerobic gas fermentation in a bioreactor, steam methane reforming, and fuel cells. NREL sees this as the way forward to large-scale hydrogen production and energy storage systems with this approach.

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[105] Audi (2017, March 7), "New Audi e-gas offer as standard: 80 percent lower CO_2 emission,"

[106] National Renewable Energy Laboratory (NREL), 'NREL + Southern California Gas'

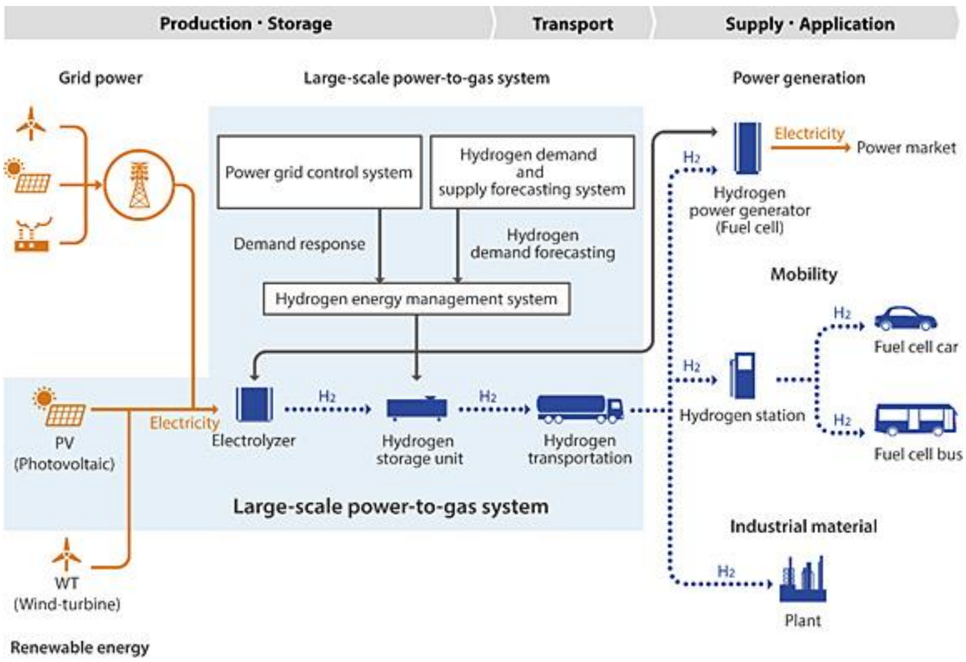
FIGURE 3-7. NREL'S BIOREACTOR

Source: NREL

3.3.1.1 NEDO (Japan)

In Japan, the New Energy and Industrial Technology Development Organization (NEDO) is the primary agency that assists the private sector in pursuing R&D on CO_2-free hydrogen production and utilization. In 2017, after reviewing six feasibility studies on PtG with different themes, NEDO chose three PtG demonstration projects which pursue technology development and will be continued through fiscal year 2020.[107] In one noteworthy project, Toshiba Energy Systems & Solutions Corporation, Tohoku Electric Power Co., Inc. and Iwatani Corporation started Fukushima Hydrogen Energy Research Field, a large-scale PtG system, in August 2018 (Figure 3-8).[108] In this field, a 10 000 kW class hydrogen production facility with the world's largest electrolysis unit will produce and store up to 900 tons of hydrogen per year, using renewable energy, with planning to commence in 2020. The project applies a new control system to coordinate overall operation of the hydrogen energy management system, the power grid control system, and the hydrogen demand/supply forecasting system so that production and supply/demand of hydrogen would be optimized.

FIGURE 3-8. NEDO'S PTG DEMONSTRATION PROJECT (FUKUSHIMA HYDROGEN ENERGY RESEARCH FIELD)



Source: NEDO

[107] NEDO, (2017, August 1), https://www.nedo.go.jp/news/press/AA5_100810.html (*in Japanese*)

[108] NEDO, (2018, August 9), 'NEDO, Toshiba, Tohoku Electric Power and Iwatani Start Construction of Fukushima Hydrogen Energy Research Field'

3.3.2 FCEV and hydrogen refuelling station

Fuel cell powered vehicles have similar characteristics to conventional ICE vehicles in terms of refuelling time and range, which means consumers could use an FCEV in a similar way as using a conventional car. However, one of the constraints on penetration of FCEV is the hydrogen refuelling infrastructure. There were around more than 200 hydrogen refuelling stations worldwide[109] by mid-2017, most of which were located in Japan, Germany, and California. Based on announced plans, the world is expected to have around 5 300 hydrogen refuelling stations by 2030,[110] about half of which will be in the Asia Pacific region. The infrastructure of hydrogen refuelling stations is tremendously lagging behind that of BEVs. In 2017, there were already 112 000 publicly accessible fast charging EVSE worldwide, and the number is expected to become 3 - 4 million[111] by 2030. Together with slower chargers, by 2030 the total publicly accessible EVSE is estimated to be 8 - 30 million units.[112] Furthermore, 125 - 250 million units of private charging EVSE are projected to be added to the BEV charging infrastructure by 2030.[113]

One of the reasons for hydrogen refuelling stations' slow build-up is their high initial cost. Currently the cost of a hydrogen refuelling station is around US$2.1 - 3 million in California,[114] and around US$3.5 - 4.5 million in Japan, [115] while the cost of fast charging EVSE is around US$30 000 - 150 000 in Japan.[116] According to IEA's estimation, in the current hydrogen business model, the hydrogen refuelling station will have to endure 10 - 15 years of negative cash flow ("valley of death").[117] Nowadays, hydrogen refuelling stations have to rely on government subsidies to sustain their business.

Besides the hydrogen supply infrastructure, the cost of the FCEV itself is also very high compared with an ICE or BEV. The price for Toyota's FCEV model, Mirai, is around US$62 400 (7 million Japanese yen (JPY)) without government subsidy, and around US$44 577 (JPY5 million) after various government subsidies, while one of the popular BEV models, Nissan Leaf, is priced around US$26 000 - 36 000 (JPY3 - 4 million) even without subsidies.

3.3.3 Integration of FCEV and the electric power grid: PtG

Since the FCEV is powered by a fuel cell, it can also be used to supply household electricity demand as a BEV does (for example, in Honda FCEV-to-home demonstration project). However, the integration of an FCEV and the associated hydrogen supply infrastructure with the electric power grid could be more flexible. Because hydrogen can be produced by water electrolysis, and the application of hydrogen is not limited to power generation but also includes transportation (FCEV), industrial use, and building co-generation units (stationary fuel cells), hydrogen can play an important role in coupling different energy sectors. Producing hydrogen with renewable power and using the

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[109] IEA (2017b), Global Trends and Outlook for Hydrogen, Paris: OECD/IEA

[110] Numbers compiled in Hydrogen Council (2017), *Hydrogen Scaling Up*

[111] The low end is based on the IEA New Policies Scenario while the higher end is based on the EV30@30 scenario pledged by the Electric Vehicles Initiative countries, both of the numbers are quoted from the IEA (2018), *Global EV Outlook 2018: Towards cross-modal electrification*

[112] IEA (2018), Global EV Outlook 2018 Towards cross-modal electrification, Paris: OECD/IEA

[113] Ibid

[114] IEA (2017b), op. cit.

[115] Small scale hydrogen refueling station (300 Nm^3/h); Source of cost data is from the Ministry of Economy, Trade and Industry, Japan (2016), *Hydrogen and Fuel Cell Roadmap*

[116] Japan Ministry of Economy, Trade and Industry, (2016),'Research on the EV/PHV Charging Infrastructure', http://www.meti.go.jp/meti_lib/report/H28FY/000026.pdf

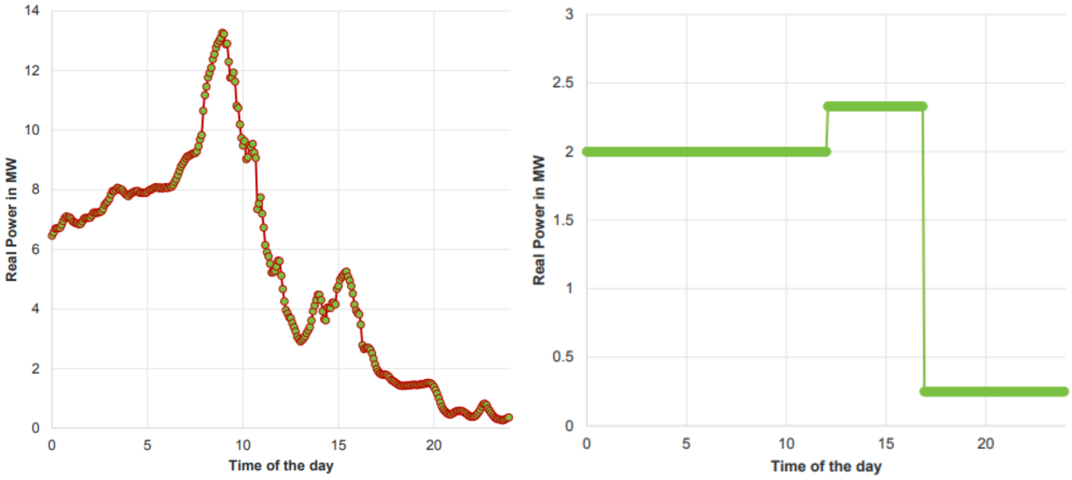
[117] IEA (2015), Technology Roadmap Hydrogen and Fuel Cells, Paris: OECD/IEA

renewable hydrogen to substitute for fossil fuel in end use sectors is expected to be one of the options for decarbonisation of the whole energy system.

The combination of renewable power and hydrogen can also contribute to grid integration of variable renewable technologies, which is a major integral part of the so called "Power-to-Gas" system. A study on the role of electrolyzers in the electric power grid carried out by the US Department of Energy (DOE) (National Renewable Energy Laboratory (NREL) and the Idaho National Lab) found that electrolyzers with appropriate controls are effective in enhancing grid stability when there is a fault in the grid.[118]

The study modelled a 13 MW electrolyser to supply the hydrogen demand for 7 200 FCEVs (hydrogen demand 1 800 kg/day) in the San Francisco and other cities nearby. The electricity for hydrogen production is from wind power and solar PV. By managing the operation of the electrolyser and hydrogen storage, the system could meet hydrogen demand for FCEVs while supplying fixed and predictable renewable electricity to the grid (Figure 3-9).

FIGURE 3-9. WIND AND SOLAR PV OUTPUT WITHOUT ELECTROLYSER (LEFT) AND AGGREGATED OUTPUT WITH PART OF THE OUTPUT ABSORBED BY THE ELECTROLYSER (RIGHT)



Source: Hovsapian, R. (2017)[119]

Although the cost of hydrogen production from renewable electricity is higher than other technologies such as natural gas steam reforming with carbon capture and sequestration (CCS), the revenue flows could be more diversified. Besides sales of hydrogen, the revenue of the system could also come from sales of renewable electricity to the grid, the sales of oxygen by-products, as well as provision of grid ancillary service. For example, a study of the PtG business model in Japan[120] found that by providing grid ancillary service and sales of oxygen, the cost of hydrogen production from water electrolysis using renewable power could be reduced from JPY36/Nm^3 (US$0.32/Nm^3) to JPY29/Nm^3 (US$0.26/Nm^3) (Figure 3-10).

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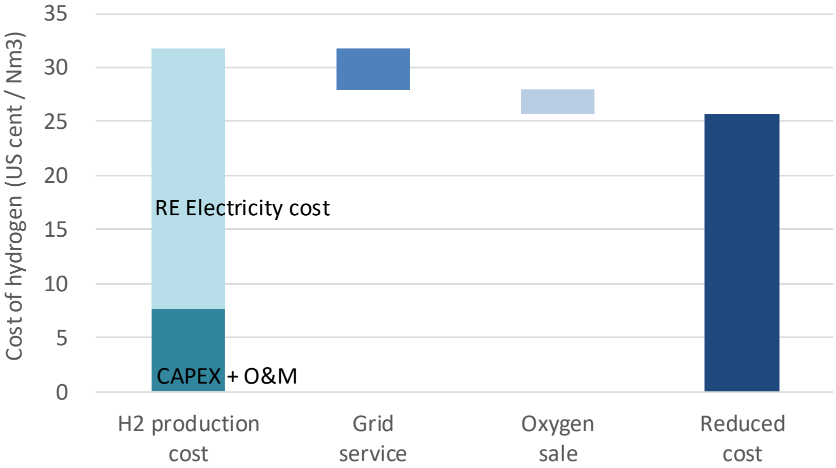
[118] Hovsapian, R., Ph. D. (US Department of Energy) (2017), 'Role of Electrolyzers in Grid Services', https://www.energy.gov/sites/prod/files/2017/06/f34/fcto_may_2017_h2_scale_wkshp_hovsapian.pdf

[119] Ibid

[120] Shibata,Y. (2018), 'Business model of "Power-to-Gas" in various timespan – provision of grid service, various applications of PtG, and its contribution to renewable scale-up', IEEJ research report

FIGURE 3-10. HYDROGEN PRODUCTION REDUCTION EFFECT BY DIVERSIFICATION OF REVENUE

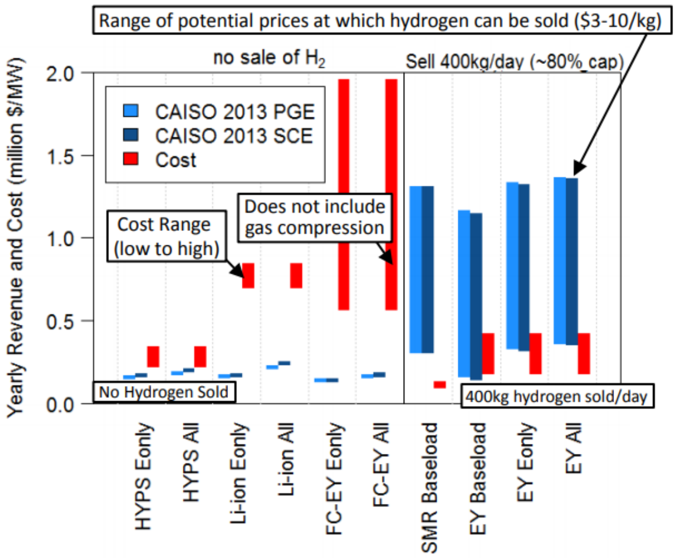


Note: Using excess renewable electricity for hydrogen production; cost of excess renewable electricity is JPY4/kWh (US$0.04/kWh); capacity factor of the electrolyser is 30%; oxygen price is JPY 5/Nm^3 (US$0.04/Nm^3)

Source: Shibata, Y. (2018)

Another study[121] on the economics of various grid service options found that by selling hydrogen, the cost competitiveness of using an electrolyser for grid ancillary service could be dramatically improved (Figure 3-11).

FIGURE 3-11. COST-REVENUE OF VARIOUS OPTIONS FOR GRID ANCILLARY SERVICE



Name	Technology
HYPS	Pumped Hydro
Li-Ion	Lithium-Ion
FC	Fuel Cell
EY	Electrolyzer
SMR	Steam Methane Reformer

Name	Services
All	All Ancillary Services
Eonly	Energy Arbitrage only
Baseload	"Flat" operation

Source: John Ericman, PhD (NREL) (2015)

The above two studies suggest that if the main purpose of electrolyser is for hydrogen production providing grid ancillary service could help reduce hydrogen production cost. On the other hand, if the main purpose is for grid stability, the sales of hydrogen could greatly improve the economic viability of the electrolyser.

Another advantage of using hydrogen for grid balancing is that it is suitable to deal with the seasonal changes in renewable energy. While a battery is flexible and almost has no site constraints, it is

[121] Ericman, J., PhD (NREL) (2015), 'Hydrogen Energy Storage (HES) and Power-to-Gas Economic Analysis', presentation at CHBC summer summit, https://www.nrel.gov/docs/fy15osti/64833.pdf

unable to provide inter-seasonal or seasonal energy storage. When renewable energies become the mainstream technology in the power supply system, back up for seasonal changes in renewable power output is necessary. Hydrogen could play a significant role in maintaining a stable power supply in a system with a high share of variable renewables.

Although the investment for hydrogen supply infrastructure is high, the applications of hydrogen are for more than FCEVs. Therefore, further improvement of the cost competitiveness of FCEVs not only requires a cost reduction of the FCEV itself but also the further scale up of other hydrogen applications, which is necessary to bring down the hydrogen fuel cost.

4 Impact of BEV and FCEV on CO_2 emissions

This chapter looks at the impact of BEV and FCEV on decarbonisation of the transport sector. The impact is evaluated by quantitative analysis, which is based on the results and assumptions of APEC Energy Demand and Supply Outlook 6th Edition published by APERC.[122]

In the 6th *Outlook*, there are several scenarios for energy demand and the calculation in this chapter utilizes the results and assumptions for the following scenarios:

> **BAU scenario**: Business-as-Usual scenario
>
> **ALT scenario**: High efficiency scenario (enhanced energy efficiency), for the transport sector, improved fuel economy for the ICE vehicle, and higher penetration of BEV and FCEV than other scenarios
>
> **HiRE scenario**: High renewable scenario (doubling renewable use in power and more biofuel in the transport sector)

By looking at the difference in CO_2 emissions between different projection scenarios, this chapter first looks at the potential for CO_2 emission reduction from various decarbonisation options for the mobility sector in the APEC region: fuel economy improvement, and fuel switching from fossil fuel to electricity or hydrogen. Furthermore, the CO_2 emission reduction effect of various options, namely, high efficiency ICE vehicles, BEV, and FCEV for different economies will be examined. Because the application of batteries in heavy duty vehicles is still facing much uncertainty this study only focuses on light duty vehicles (LDV).

4.1 Methodology

4.1.1 Estimation of CO_2 emission reduction effect from the decarbonisation of LDVs

Decarbonisation of the mobility sector can be achieved by fuel economy improvement of ICE cars, fuel switching from fossil fuel to electricity, or hydrogen. This study estimates the marginal CO_2 emission impact per decrease of ICE gasoline LDV, per increase of BEV, and per increase of FCEV by comparing the difference of car stock and associated fuel consumption between various scenarios.

The CO_2 emission reduction per decrease of ICE gasoline vehicle is estimated by comparing the difference of ICE gasoline vehicle stock and the associated CO_2 emission from ICE gasoline vehicles between the BAU scenario and the ALT scenario. The associated CO_2 emission is the product of gasoline consumption and the CO_2 emission ratio of gasoline.

Because of the decarbonisation of ICE LDV fleet comes from both the substitution of gasoline ICE vehicles and the improvement of fuel economy, the result represents the effect of the two options.

For BEV and FCEV, it should be noted that though on-road CO_2 emissions are close to zero, the CO_2 emissions associated with power generation or hydrogen production and delivery need to be counted. The CO_2 emission increase per BEV car is calculated in a similar way as that of the ICE car. However, because of the difference in the power generation mix, more a decarbonized power system means less additional CO_2 emissions from BEV. To examine the impact of power sector's decarbonisation on BEV's carbon intensity, two CO_2 emission rates of the power generation are used.

[122] Asia Pacific Energy Research Centre (APERC) (2016), *APEC Energy Demand and Supply Outlook 6th Edition*, https://aperc.ieej.or.jp/publications/reports/outlook.php

One of the CO_2 emission rate of power generation is estimated from BAU scenario, the other is from HiRE scenario.

In the calculation of CO_2 emission increase per FCEV the CO_2 emission associated with hydrogen production and delivery is counted. Different hydrogen production and delivery methods will result in different CO_2 emission intensity for hydrogen (Table 4-5). This study assumes that FCEV fuel is supplied from domestic sources. For economies with CCS potential, hydrogen is assumed to come from renewable power water electrolysis, or fossil fuel plus CCS. For an economy with little CCS potential, hydrogen comes from renewable power water electrolysis or on-site steam reforming. Compressed hydrogen is assumed to be the method for domestic delivery of hydrogen.

4.1.2 Carbon footprint of various low carbon options

In this section, the carbon footprint (CO_2 emission per km) of several decarbonisation options for the mobility sector, namely high efficiency ICE gasoline LDV, BEV and FCEV are estimated. The carbon footprint is calculated based on fuel economy (fuel consumption per km) of each kind of vehicle and the CO_2 emission rate of the associated fuel. Assumptions for fuel economy are from the Efficiency Improvement Scenario of the 6th *Outlook*.

To examine the impact of the power generation mix on the carbon footprint of BEVs and hydrogen production and delivery on FCEVs, this study assumes two types of power generation mix and two hydrogen supply options with different CO_2 emission rates. The CO_2 emission rate for power generation is calculated based on the power generation mix from the ALT scenario (High case) and HiRE scenario (Low case) (Table 4-4). The high case for the CO_2 emission rate for hydrogen is based on the on-site steam reforming, and the low case based on electrolysis from renewable power with compressed hydrogen for delivery and filling (Table 4-5). However, it should be noted that while the CO_2 emission during the delivery and filling process of hydrogen is counted, the CO_2 emission associated with gasoline delivery (for ICE cars) and electricity transmission loss (for BEV) are not counted.

TABLE 4-1. ASSUMPTIONS FOR CO_2 EMISSION RATE OF VARIOUS MOBILITY FUELS

	High case	Low case
Gasoline	0.0693 kg-CO_2/MJ	
Electricity	CO_2 emission rate of the power sector in **ALT scenario**	CO_2 emission rate of the power sector in **HiRE scenario**
Hydrogen	1.38 kg-CO_2/Nm^3-H_2 (on site steam reforming)	0.55 kg-CO_2/Nm^3-H_2 (RE electrolysis and compressed hydrogen for delivery and filling)

Source: APERC (2016), CO_2 free Hydrogen Committee (2018)

4.2 Preconditions and assumptions

4.2.1 LDV stock in the APEC region in 2040

ICE cars will continue to be the main means of mobility in the future. The stock of gasoline type ICE LDVs in APEC is projected to reach 648 million in 2040 up from 556 million in 2015 under the BAU scenario. Under the ALT scenario, due to higher penetration of BEVs and FCEVs and other types of clean fuel vehicles, the stock of ICE gasoline LDVs will be 575 million in 2040, still higher than that of 2015, but 73 million less than that under the BAU scenario.

However, when looking at ICE gasoline LDV stock by economy, some economies, like, Brunei Darussalam; Hong Kong, China; Japan; Korea; Russia; Singapore; Chinese Taipei; and the United States, will see a decrease of ICE gasoline LDVs from 2015 to 2040 even under the BAU scenario (Table 4-2). The major reason is decreasing car ownership.

In 2015 there are more than 0.4 million BEVs in the APEC region. Under the BAU scenario the region is expected to see 29 million of BEVs in 2040, and under the ALT scenario there are projected to be 20 million more BEVs than the BAU scenario. Almost all APEC economies are expected to experience an increase of BEVs from 2015 to 2040.

TABLE 4-2. STOCK OF ICE GASOLINE, BEV AND FCEV LDVS IN APEC, 2040, BAU AND ALT SCENARIOS

THOU.	ICE GASOLINE			BEV			FCEV		
	2015	BAU 2040	ALT 2040	2015	BAU 2040	ALT 2040	2015	BAU 2040	ALT 2040
AUS	13,304	16,712	15,223	0	166	588	-	1.9	23.7
BD	153	135	125	0	8	14	-	-	-
CDA	21,280	22,368	19,443	35	423	1,227	-	6.6	45.2
CHL	3,094	4,583	3,813	1	100	331	-	-	-
PRC	81,354	151,776	142,202	139	13,748	15,496	-	-	1,804.7
HKC	463	416	364	0	6	9	-	-	-
INA	14,877	55,416	53,816	-	2,044	2,558	-	-	-
JPN	63,640	47,015	31,080	94	1,897	4,137	-	91.3	138.7
ROK	9,750	8,777	7,912	3	365	697	-	-	62.1
MAS	11,937	13,132	12,302	5	451	580	-	-	-
MEX	28,129	36,640	34,902	-	402	1,164	-	-	-
NZ	2,626	2,725	2,584	0	43	59	-	3.2	4.1
PNG	30	181	181	-	-	-	-	-	-
PE	1,613	6,291	5,671	5	264	913	-	-	-
RP	1,846	5,751	5,459	1	368	503	-	-	-
RUS	43,508	42,545	38,247	21	1,605	5,562	-	-	-
SIN	647	465	389	0	33	79	-	-	-
CT	6,384	3,871	3,446	3	215	385	-	-	23.1
THA	4,554	9,763	9,232	7	797	1,134	-	-	-
USA	246,132	213,845	184,359	109	5,623	13,268	0.6	132.8	578.9
VN	465.0	5,741.7	4,539	-	-	490	-	-	-

Note: AUS = Australia; BD = Brunei Darussalam; CDA = Canada; CHL = Chile; PRC = China; HKC = Hong Kong, China; INA = Indonesia; JPN = Japan; ROK = Korea; MAS = Malaysia; MEX = Mexico; NZ = New Zealand; PNG = Papua New Guinea; PE = Peru; RP = the Philippines; RUS = Russia; SIN = Singapore; CT = Chinese Taipei; THA = Thailand; USA = the United States; VN = Viet Nam; number

Source: APERC (2016)

Compared with BEVs the adoption of FCEVs is much smaller, only 630 in 2015. In 2040, the number of FCEVs will be 236 000 under BAU scenario, and under the ALT scenario the number is expected to be 2.7 million units, more than 10 times of that of BAU. However, even under the ALT scenario only a few economies will adopt FCEVs: Australia; Canada; China; Japan; Korea; New Zealand; Chinese Taipei; and the United States.

4.2.2 Assumptions on energy intensity and CO_2 emission rate

The following tables (Table 4-3 and Table 4-4) show the assumptions on carbon intensities of various vehicle types and the CO_2 emission rate in power sector under different scenarios.

Table 4-3. Energy intensity of high efficient ICE gasoline LDV, BEV, and FCEV in APEC

	2030			2040		
	High Eff. ICE	BEV	FCEV	High Eff. ICE	BEV	FCEV
AUS	2.35	0.62	1.65	1.93	0.62	1.65
BD	2.51	0.77	2.06	2.06	0.77	2.06
CDA	1.76	1.32	1.65	1.45	1.32	1.65
CHL	1.46	0.62	1.65	1.20	0.62	1.65
PRC	1.37	0.62	1.65	1.12	0.62	1.65
HKC	1.51	0.62	1.65	1.24	0.62	1.65
INA	1.86	0.62	1.65	1.53	0.62	1.65
JPN	1.74	0.62	1.65	1.43	0.62	1.65
ROK	1.55	0.62	1.65	1.27	0.62	1.65
MAS	1.52	0.62	1.65	1.24	0.62	1.65
MEX	1.54	0.62	1.65	1.26	0.62	1.65
NZ	1.91	0.62	1.65	1.57	0.62	1.65
PNG	2.64	0.62	1.65	2.16	0.62	1.65
PE	1.55	0.62	1.65	1.28	0.62	1.65
RP	1.53	0.62	1.65	1.26	0.62	1.65
RUS	1.57	0.62	1.65	1.29	0.62	1.65
SIN	2.02	0.62	1.65	1.65	0.62	1.65
CT	1.51	0.62	1.65	1.24	0.62	1.65
THA	1.58	0.62	1.65	1.29	0.62	1.65
USA	1.77	0.62	1.65	1.45	0.62	1.65
VN	1.46	0.62	1.65	1.20	0.62	1.65

Note: AUS = Australia; BD = Brunei Darussalam; CDA = Canada; CHL = Chile; PRC = China; HKC = Hong Kong, China; INA = Indonesia; JPN = Japan; ROK = Korea; MAS = Malaysia; MEX = Mexico; NZ = New Zealand; PNG = Papua New Guinea; PE = Peru; RP = the Philippines; RUS = Russia; SIN = Singapore; CT = Chinese Taipei; THA = Thailand; USA = the United States; VN = Viet Nam; units are MJ/km

Source: APERC (2016)

TABLE 4-4. CO_2 EMISSIONS RATE OF THE POWER SECTOR IN APEC; BAU, ALT AND HIRE SCENARIOS

	2030			2040		
	BAU	ALT	HiRE	BAU	ALT	HiRE
AUS	0.559	0.564	0.337	0.441	0.420	0.248
BD	0.408	0.392	0.367	0.398	0.401	0.368
CDA	0.096	0.059	0.073	0.091	0.037	0.055
CHL	0.425	0.357	0.233	0.433	0.345	0.231
PRC	0.530	0.504	0.479	0.491	0.442	0.426
HKC	0.758	0.849	0.748	0.564	0.596	0.556
INA	0.720	0.681	0.537	0.736	0.688	0.451
JPN	0.368	0.341	0.329	0.393	0.365	0.358
ROK	0.420	0.383	0.369	0.406	0.360	0.351
MAS	0.593	0.583	0.548	0.585	0.572	0.543
MEX	0.377	0.367	0.364	0.369	0.352	0.351
NZ	0.073	0.047	0.014	0.072	0.034	0.015
PNG	0.519	0.485	0.180	0.594	0.567	0.312
PE	0.228	0.183	0.128	0.232	0.170	0.156
RP	0.682	0.640	0.500	0.709	0.640	0.545
RUS	0.464	0.444	0.412	0.418	0.386	0.353
SIN	0.369	0.369	0.363	0.369	0.368	0.363
CT	0.602	0.625	0.563	0.583	0.606	0.538
THA	0.487	0.468	0.422	0.488	0.464	0.407
USA	0.392	0.392	0.268	0.385	0.384	0.253
VN	0.502	0.486	0.439	0.612	0.606	0.526

Note: AUS = Australia; BD = Brunei Darussalam; CDA = Canada; CHL = Chile; PRC = China; HKC = Hong Kong, China; INA = Indonesia; JPN = Japan; ROK = Korea; MAS = Malaysia; MEX = Mexico; NZ = New Zealand; PNG = Papua New Guinea; PE = Peru; RP = the Philippines; RUS = Russia; SIN = Singapore; CT = Chinese Taipei; THA = Thailand; USA = the United States; VN = Viet Nam; units are gCO_2/kWh

Source: APERC (2016)

The assumptions for CO_2 emission rate of hydrogen by different production and delivery/storage methods are given in Table 4-5. Although CO_2 emission intensity of hydrogen supply varies from economy to economy because of a lack of data availability, this study applies the intensity in Table 4-5 to all the economies.

TABLE 4-5. CO_2 EMISSIONS RATE OF VARIOUS HYDROGEN PRODUCTION AND DELIVERY/FILLING OPTIONS

On/Off-site	Hydrogen Production Technologies	Production	Delivery, Storage	Filling	Total
On-site	Town Gas Reforming	1.08	-	0.30	1.38
	Sewage Sludge Gas Reforming	0.31	-	0.30	0.60
Off-site	Natural Gas Reforming, Compressed Hydrogen Transport	1.07	0.25	0.3	1.62
	Natural Gas Reforming, Liquefied Hydrogen Transport	1.07	0.63	0.16	1.86
	By-Product Hydrogen, Compressed Hydrogen Transport	-	0.25	0.30	0.55
	By-Product Hydrogen, Liquefied Hydrogen Transport	-	0.63	0.16	0.79
	Natural Gas Reforming + CCS, Compressed Hydrogen Transport	0.45	0.25	0.30	1.00
	Natural Gas Reforming + CCS, Liquefied Hydrogen Transport	0.45	0.63	0.16	1.24
	Electrolysis using Wind Power, Compressed Hydrogen Transport	-	0.25	0.30	0.55
	Electrolysis using Wind Power, Liquefied Hydrogen Transport	-	0.63	0.16	0.79
	Electrolysis using PV, Compressed Hydrogen Transport	-	0.25	0.30	0.55
	Electrolysis using PV, Liquefied Hydrogen Transport	-	0.63	0.16	0.79

Note: units are kg-CO_2/Nm^3-H_2, numbers are for Japan

Source: Adapted from CO_2 free Hydrogen Committee (2018)[123]

4.3 Estimation results

4.3.1 Marginal CO_2 emission reduction effect

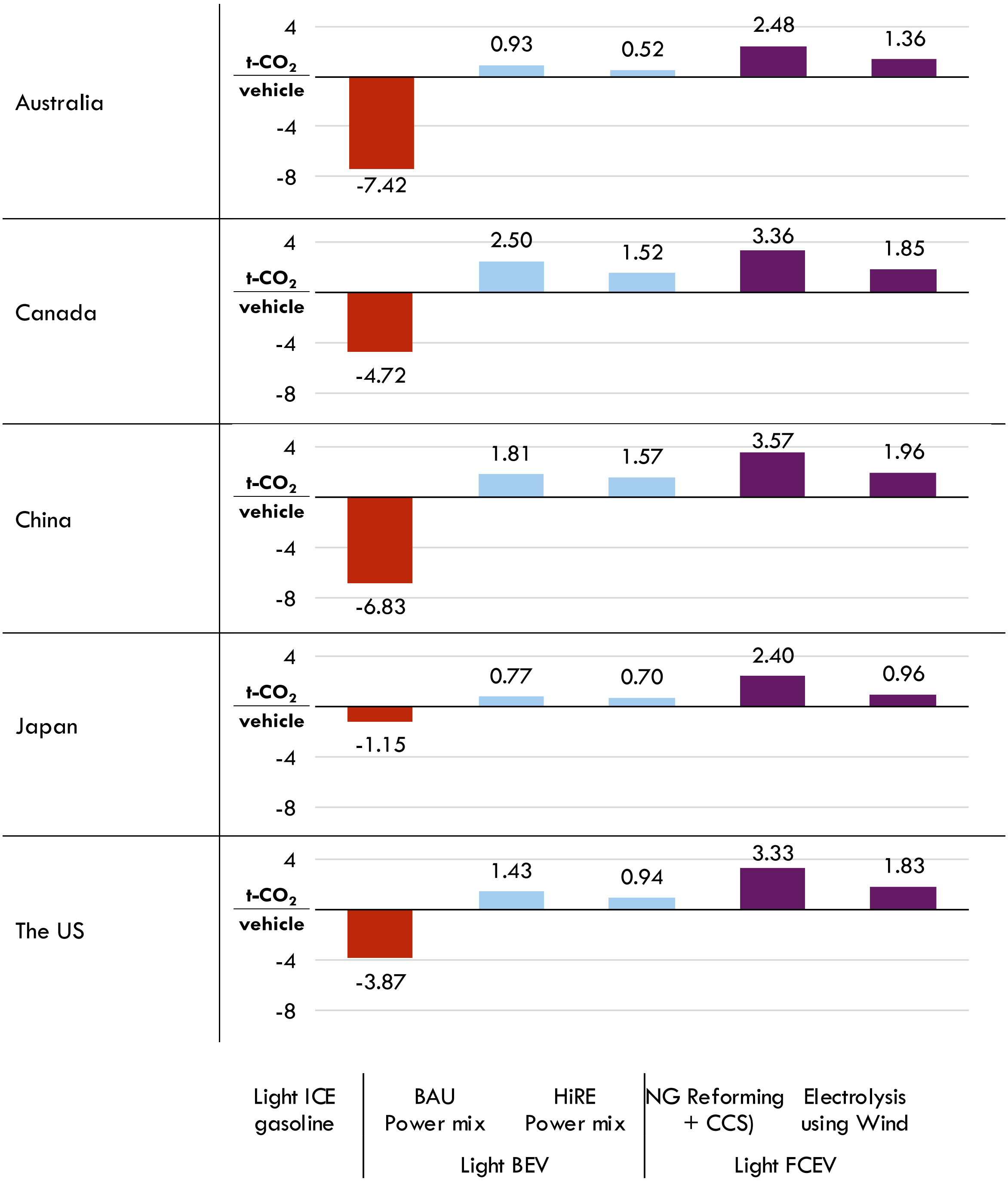
The estimation results (Figure 4-1) show that for all the economies the CO_2 emission reduction effect per ICE gasoline LDV is larger than the CO_2 emission increase effect per BEV. This indicates that fuel economy improvement of ICE cars as well as substitution of ICE cars with BEVs could result to overall CO_2 emission reduction. However, since the CO_2 emission reduction per ICE car comes from both the fuel economy improvement and substitution (ICE being substituted by other types of cars) it is hard to tell whether CO_2 emissions will decrease or increase when replacing ICE gasoline LDV with BEV from the results shown in Figure 4-1. The carbon footprint comparison of different type of cars will be discussed in the following section 4.3.2.

As for FCEV, as far as the hydrogen fuel is produced by clean means, steam reforming plus CCS or water electrolysis using renewable electricity, the CO_2 emission increase per FCEV is smaller than the CO_2 emission reduction effect per ICE gasoline LDV. Improvement of fuel economy as well as moving from ICE cars to FCEVs using clean hydrogen could also contribute to the decarbonisation of the mobility sector. However, if the hydrogen is produced from fossil fuel without CCS (for example on-

[123] CO_2 free Hydrogen Committee, organized by the Ministry of Economy, Trade and Industry (METI), Japan (2018), 'Report on CO_2 free Hydrogen', https://www.meti.go.jp/report/whitepaper/data/pdf/20170307001_01.pdf

site steam reforming), the CO_2 emission increase per FCEV is higher than the CO_2 emission reduction effect per ICE car (Figure 4-1), which suggests that depending on the hydrogen supply source, substitution of ICE with FCEV could result to more CO_2 emissions.

FIGURE 4-1. IMPACT ON CO_2 EMISSION BY ICE FUEL ECONOMY IMPROVEMENT, ICE REDUCTION, BEV AND FCEV IN SELECTED ECONOMIES (2040)



Notes: ※1: APERC Outlook, Road Transport Default CO_2 Emissions Factors and Uncertainty Ranges, Default value, 69300 for Motor Gasoline, 74100 for Gas / Diesel Oil;

※2: "APERC Outlook 6th_AnnexII_DataProjectionTables.xlsx", Energy-related CO_2 emissions(Mt-CO_2) from Electricity sector / Generation (TWh) of Electricity supply of each economy;

※3: Mizuho Information & Research Institute, 1.38 for Town gas reforming (onsite)

Source: APERC (2016)

4.3.2 Carbon footprint of various low carbon options

The carbon footprints of various low carbon vehicles in selected APEC economies are shown in Figure 4-1. For some of the economies shown in the results, though the 6th edition of the APEC Energy Demand and Supply Outlook projects there will be no FCEV adoption, the results indicate what the carbon footprint of an FCEV would be if FCEVs are adopted in the economy.

For most APEC economies with a low CO_2 emission rate in the power sector, such as Canada, the BEV has a significant advantage over high efficiency ICE LDV and FCEV in terms of carbon footprint. Even in economies with higher carbon intensity, like Japan, Republic of Korea, and the United States, for the power sector, BEV is still the cleanest option.

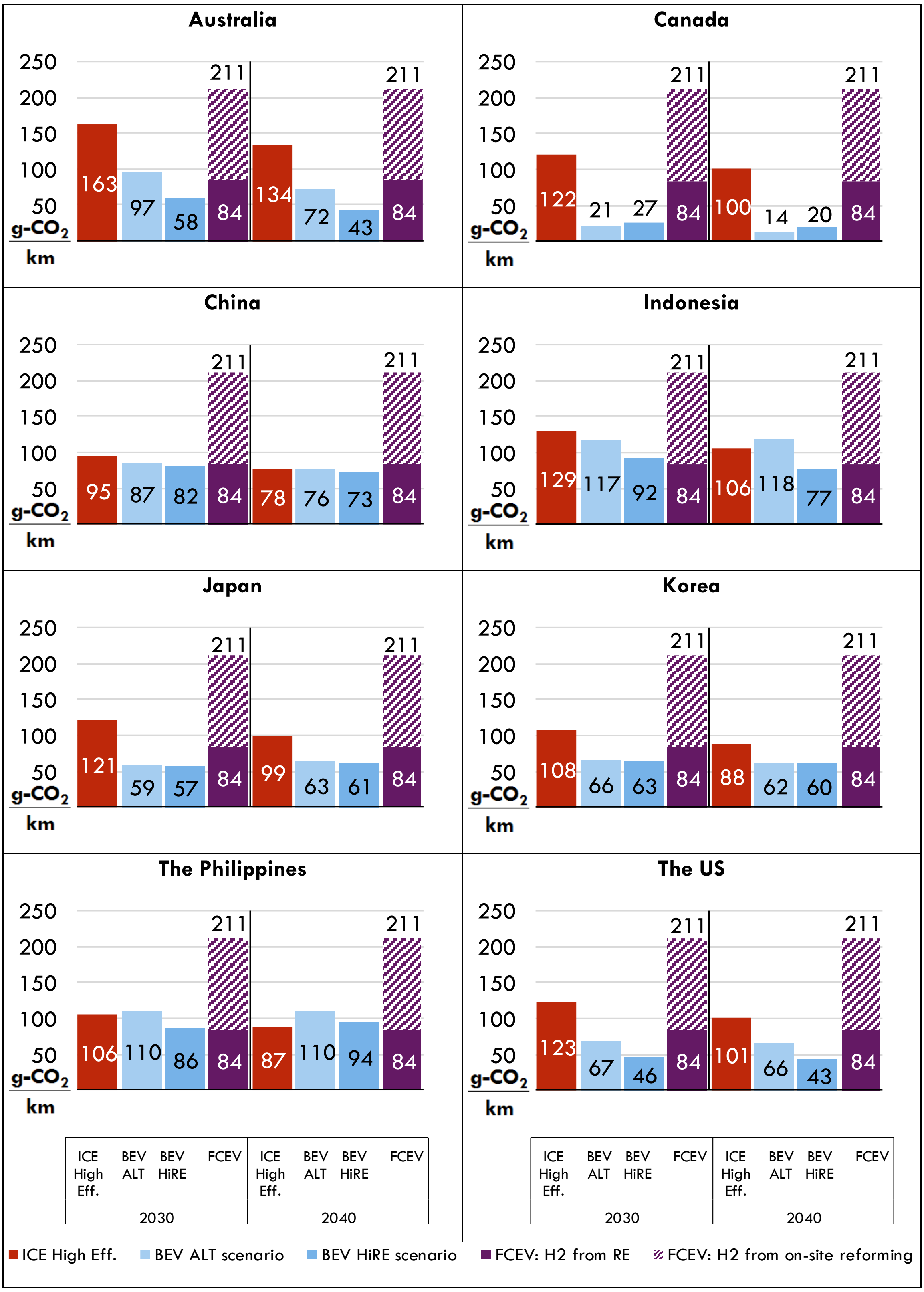
For Australia, the carbon footprint of BEV is lower than the high efficiency ICE. However, in 2030 an FCEV using hydrogen produced from renewable energy is projected to be cleaner than a BEV if the power sector does not have enough low carbon power sources like renewable energy. With the decarbonisation of the power sector, the BEV could become the cleanest option in the longer term.

In China, because the LDV market was developed later than that of high income economies, new automobile models represent most of the LDV stock, which gives the LDV fleet a relatively higher fuel economy. The carbon footprint of a BEV does not change much compared with a high efficiency ICE LDV. The carbon footprint of an FCEV with hydrogen produced from renewable power is also about the same level as a BEV and a high efficiency ICE LDV. However, if the hydrogen is supplied from on-site steam reforming, the FCEV's carbon footprint will be much higher than the other clean vehicle options.

For economies with a high carbon intensity of power generation, the carbon footprint of a BEV could be lower than that of a high efficiency ICE LDV. For example, in Indonesia in 2040 where the power generation mix was a smaller share of renewable energy, the carbon footprint of a BEV is higher than that of a high efficiency ICE LDV. Also in the Philippines, the BEV is more carbon intensive than the high efficiency ICE LDV or FCEV using hydrogen produced from renewable energy.

When considering the CO_2 emission from power generation or hydrogen production and delivery, the carbon footprint of BEVs and FCEVs is not necessarily lower than that of high efficiency ICE cars. Actually if the hydrogen is produced from fossil fuel without CCS, the carbon footprint of FCEVs could be much higher than that of high efficiency ICE cars and BEVs. In most of the economies, FCEVs using hydrogen produced from renewable energy are less carbon intensive than high efficiency ICE cars. A BEV's carbon footprint is highly dependent on the power generation mix. For economies with a low CO_2 emission rate in the power sector, substitution of ICE LDVs with BEVs could contribute to the decarbonisation of the energy system. However, in economies where the CO_2 emission rate in the power sector is high, a high efficiency ICE vehicle is a better option than a BEV in terms of CO_2 emission reduction.

FIGURE 4-2. CARBON FOOTPRINT OF CLEAN VEHICLES IN SELECTED ECONOMIES



Source: Estimated by the Institute of Energy Economics, Japan based on APERC (2016)

5 Comparative analysis of BEV/VtG and FCEV/PtG

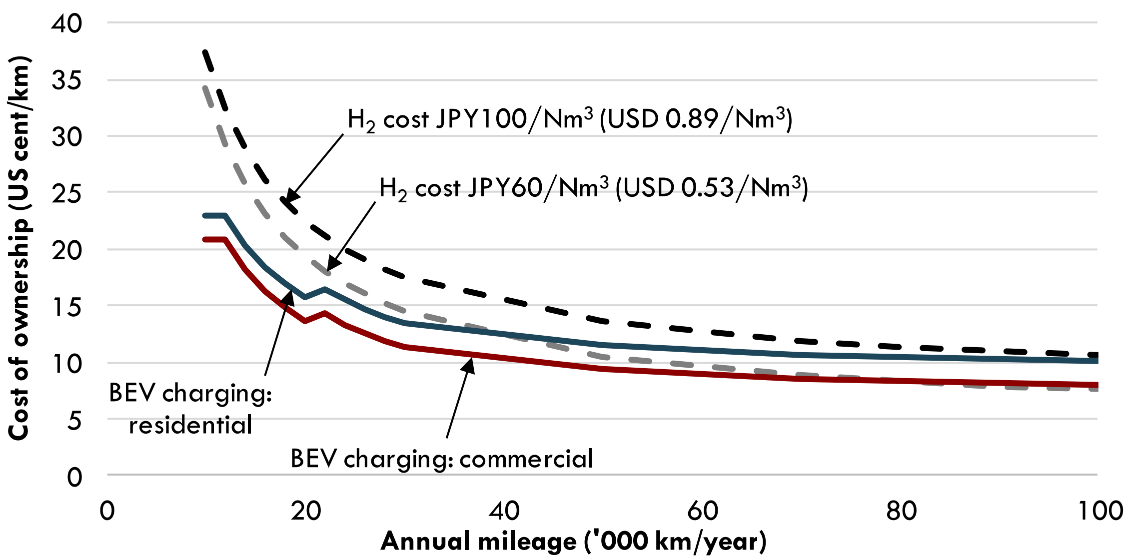
In the Chapter 2 and 3 the benefits and challenges of BEVs and FCEVs were investigated separately, and in this chapter BEVs and FCEVs are compared together in terms of their economics, their integrations with the grid, and how they can adapt to the long term transition of the transport sector. Some of the comparative analysis are taken out from a different perspective than the previous chapters and some are based on the discussions in the previous chapter.

5.1 Short-term

5.1.1 Economics of BEVs and FCEVs

Although BEV and FCEV technologies are seen as competitors, their differences in driving range, energy density, and recharging/refuelling character mean that BEVs and FCEVs can complement each other in replacing fossil fuel transport options. Given the battery's energy capacity and energy density a BEV is more suitable to replace light duty vehicles for short range use, while an FCEV can be used to replace heavy duty and longer-range transport means such as heavy duty trucks, long distance buses, etc. Besides, fuel cells can also be used to power trains, ferries, or even planes where electrification is difficult.

FIGURE 5-1 AVERAGE ANNUAL COST OF FCEV AND BEV UNDER DIFFERENT DRIVING DISTANCE



Note: Two types of fuel cost for FCEV: current price JPY100/Nm^3 (around US\$0.89/Nm^3), and future (reduced) hydrogen cost JPY60/Nm^3 (around US\$0.53/Nm^3); electricity tariff for residential charging: JPY28.5/kWh (around US\$0.25/kWh).

Source: The Institute of Energy Economics, Japan

In Japan, the price for an FCEV (Toyota Mirai) is around JPY5 million (around US\$44 577) after subsidy. The price of BEV after subsidy is around JPY3 million (around US\$26 746, for example, Nissan Leaf). The fuel economy of an FCEV and a BEV are 11.7 km/Nm^3-H_2[124] and 5 km/kWh, respectively. The life span of the vehicles are assumed to be 15 years for both type of the cars. However, BEV battery's lifespan depends on the charging/discharging cycles, or the usage of the BEV. Currently some of the BEV OEM's warranty for the battery is around 161 000 km (100 000 miles) of total driving distance, and the cost of battery replacement is around JPY60 000

[124] Estimated from Toyota Mirai's spec (5kg H_2 for 650km)

(around US$535).[125] Taking into account the battery replacement cost,[126] the average annual cost of an FCEV and a BEV over annual driving mileage are shown in Figure 5-1.

In Japan, the average annual driving distance of a private LDV is around 10 000 km.[127] Over this driving distance a BEV is much more cost competitive than an FCEV even if the hydrogen fuel cost could be reduced to JPY60/Nm^3 (around US$0.53/Nm^3) (Figure 5-1). However, for users with longer driving distances, if the hydrogen fuel cost is reduced an FCEV could become preferable to a BEV in terms of cost. If the LDV is for commercial use, the annual driving distance is much longer than that of a private LDV, more than 60 000 km in Japan.[128] Although over longer distances the cost competitiveness of an FCEV is better, the electricity tariff for a commercial BEV's charging is probably cheaper because of lower electricity tariffs (Figure 5-1). Even for longer driving distances, further cost reduction of vehicle and fuel cost is critical for FCEV to be cost competitive over BEV.

5.1.2 Grid integration

In terms of grid integration, both BEVs and FCEVs are still at an early stage. Expected grid services provided by a BEV includes: energy storage (absorbing excess power and providing power when generation is in short), operating reserves, and frequency regulation.[129] Although the minimum capacity requirement of these services varies from country to country, it is usually much larger than one individual BEV can provide. For example, the minimum capacity requirement for providing operation reserve for the Singapore grid is 1 MW.[130] The minimum capacity requirement of frequency regulation service for the grid in Japan is 10 MW.[131] As a result, BEVs have to be aggregated to meet the capacity requirement for some of the grid services.

On the other hand, the grid integration of FCEVs is quite different from that of BEVs. As stated before, the interaction of the electric power grid and FCEVs is more about electricity-hydrogen conversion than electricity to electricity exchange. At present, large scale electrolysers are still at the early stage of commercialization, but several power-to-gas demonstration projects are already underway, in which MW level electrolysers are being utilized. Given its scale advantage, power-to-gas is more suitable than BEVs to provide grid service.

5.2 Long term perspective

In the long term, with the improvement of battery performance and its cost reduction, the penetration of BEVs are expected to continue. According to IEA, BEVs are expected to account for 6% of global LDV stock by 2030[132] (New Policy Scenario). However, further scale-up of BEVs will require a breakthrough on battery energy density to enable the vehicle to cover longer driving range and to meet the increasing on-board electricity demand from data processing as the car becomes more sophisticated. Although the future of VtG has more uncertainties, as the electric power grid and

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[125] Clean Technica, https://cleantechnica.com/2014/07/01/nissan-leaf-replacement-battery-priced-5499/

[126] Assuming that after 100 000 km BEV's battery need to be replaced at the cost of JPY60 000.

[127] Survey by Ministry of Land, Infrastructure, Transport and Tourism, http://www.mlit.go.jp/jidosha/iinkai/seibi/5th/5-2.pdf

[128] Ibid

[129] Steward, D. (National Renewable Energy Laboratory) (2017),. 'Critical Elements of Vehicle-to-Grid (V2G) Economics.'

[130] Darlene Steward (National Renewable Energy Laboratory) (2017), "Critical Elements of Vehicle-to-Grid (V2G) Economics." (quoted from Ciechanowicz, D., A. Knoll, P. Osswald, and D. Pelzer. (2015), 'Towards a business case for vehicle-to-grid – maximizing profits in ancillary service markets.', Power Systems 89: 203-231.)

[131] Electricity and Gas Market Surveillance Committee, Japan (2018), 'Results of the public bidding for balancing power by the general utility companies.'

[132] IEA (2018), Global EV Outlook 2018 Towards cross-modal electrification, Paris: OECD/IEA

consumer side energy management get smarter, bi-directional electricity flow between the BEV and the grid is expected to become easier.

On the other hand, the prospect of FCEVs depends not only on the fuel cell vehicle's performance and cost, but also on the hydrogen supply chain. To drive down the cost of hydrogen supply infrastructure, the market for hydrogen application needs to be expanded. According to the Hydrogen Energy Council's scenario, by 2050 hydrogen could supply 18% of the world energy demand.[133] With the expansion of hydrogen applications and cost reduction, the council envisioned that hydrogen could power more than 400 million cars, 15 - 20 million trucks, and around 5 million buses by 2050.[134] Given the time needed to build up hydrogen infrastructure the penetration of FCEVs will take longer than for BEVs. Some of the APEC economies, like Japan, United States, and the People's Republic of China are projected to be the major markets for fuel cell vehicles (including LDV, trucks, and buses).

In the longer term the transport sector itself is projected to experience radical change, which will also affect the development of BEVs and FCEVs. Various think tanks and automobile OEMs predict that in the future how people use or own their cars will be different than today, with autonomous driving and car sharing the two most important characteristics of future mobility. McKinsey & Co forecast that full autonomous driving will arrive by 2030 at the earliest and with greater adoption later on,[135] the firm also projected that in 2030 nearly 1 in 10 new private cars sold would be shared vehicle.[136]

One of the implications of the transformation of mobility service is that as vehicles become a tool for mobility service rather than a personal property, on-road time will become longer than for personal vehicles. The change in the car utilization rate means that driving distance and thus energy demand for an individual car will both become much more than the present level. Besides, autonomous driving also demands more electricity to power the tremendous data processing on-board the car. All of these require more on-board energy supply in an individual car, which means higher energy density in the powertrain. Although BEVs have more cost advantages over FCEVs, in terms of energy density FCEVs are better positioned than BEVs in the future mobility system.

5.3 Policy implications

The APEC region is both the largest market and the technology/industry development centre of BEV and FCEV. In 2017, APEC economies held 79% and 80% of global BEV and FCEV stocks, respectively. At present, BEVs are enjoying more government support. Seven economies have announced targets for BEV development and more than 10 economies have policy support for BEV. However, only China; Japan; Korea; and the US (California) have set roadmaps for FCEV development.

The BEV costs, both the vehicle itself and the associated infrastructure, is lower compared with FCEVs, which is one of the major reasons why BEVs is more popular over FCEVs at present. BEVs are flexible to interact with the existing electricity grid but are facing difficulties in providing effective grid stability service because of their small scale, and unpredictability in grid connection, etc. On the other hand, if hydrogen is supplied from renewable energy to FCEVs, FCEVs can interact with the electricity through the Power-to-Gas system, which not only can provide firm and larger scale grid service but

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133 Hydrogen Council (2017), 'Hydrogen scaling up A sustainable pathway for the global energy transition'

134 Ibid

135 Mckinsey & Co, https://www.mckinsey.com/features/mckinsey-center-for-future-mobility/overview/autonomous-driving

136 Mckinsey & Co (2017), "How shared mobility will change the automotive industry", https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/how-shared-mobility-will-change-the-automotive-industry

also can serve coupling the renewable power with other sectors that are difficult to be electrified, including heave duty transport modes. PtG and FCEVs are expected to play an important role for deep decarbonisation.

In terms of impact on CO_2 emission reduction, whether and how the BEVs and FCEVs can contribute to the energy system's decarbonisation depends on the carbon intensity of the power systems and hydrogen supply chain. Promotion of BEVs need to be coupled with a due effort on decarbonisation of the power sector (by introducing more low carbon power generation technologies) to make BEVs a cleaner substitution to ICE cars. However, for FCEVs contribute to the energy system's decarbonisation, not only hydrogen should be produced by cleaner options (at present hydrogen is produced from fossil fuel) but the CO_2 emission over the hydrogen delivery and storage needs also to be reduced.

Given BEVs and FCEVs' different cost and technology characteristics, as well as the variation on economies' social, economic, and energy situation, the pathway towards BEVs/FCEVs penetration will be quite different from economy to economy. Given the diversity, cooperation within the region can be effective to help accelerating the penetration of BEVs/FCEVs. For example, some economies may serve as market, others as technology supplier/production hub, while others resource supplier (in the case of hydrogen). Besides, cooperation on standardization, such as standards on charging facilities, VtG associated standards, standards on low carbon hydrogen supply chain, etc., is also important for facilitating the scaling up of BEVs/FCEVs adoption.

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