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Energy Storage for Renewable Energy Integration in ASEAN and East Asian Countries: Prospects of Hydrogen as an Energy Carrier vs. Other Alternatives

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Chapter 1

Introduction

The strategic measures in the Association of Southeast Asian Nations (ASEAN) Plan of Action for Energy Cooperation 2016–2025 include increasing the share of renewable energy to a mutually agreed percentage in the ASEAN energy mix (total primary energy supply) by 2020. However, a critical barrier is the intermittency of renewables, especially solar and wind energy.

The energy system, including the power grid, needs significant energy storage capacity to fully absorb renewable energy. Otherwise, harvested renewable energy will be abandoned, resulting in the sheer waste of energy and money by countries that have already heavily invested in intermittent renewables.

Pumped hydropower is a low-cost energy storage solution, but its potential is limited by geological conditions. The other solution is large-scale battery storage, but batteries have high capital expenditure (CAPEX) and operational expenses (OPEX), a short lifetime (5–7 years), and fixed and limited storage capacity that degrades continuously (Khalili et al., 2019).

Hydrogen (H_2) does not typically occur in nature on Earth, but it could be produced using various physical and chemical processes, which consume energy in various forms. When high-purity hydrogen is consumed to acquire energy (especially by using fuel cell technologies), it is considered an energy carrier. As consumption of hydrogen as an energy carrier typically produces pure water (H_2O), hydrogen is considered clean energy, especially if it is produced from renewable energy–based pathways. Hydrogen thus has the potential to cure our dependence on fossil fuel and eliminate greenhouse gas (GHG) emissions.

Hydrogen as an energy carrier has many advantages:

(i) Its energy intensity is higher than that of gasoline; 5 kilograms (kg) of hydrogen can power a passenger vehicle for up to 500 kilometres (km).

(ii) Refuelling can be done as quickly as for gasoline and diesel. These first two advantages make hydrogen especially suitable for long-distance or heavy-duty trips, for example, by intercity buses and cargo delivery trucks.

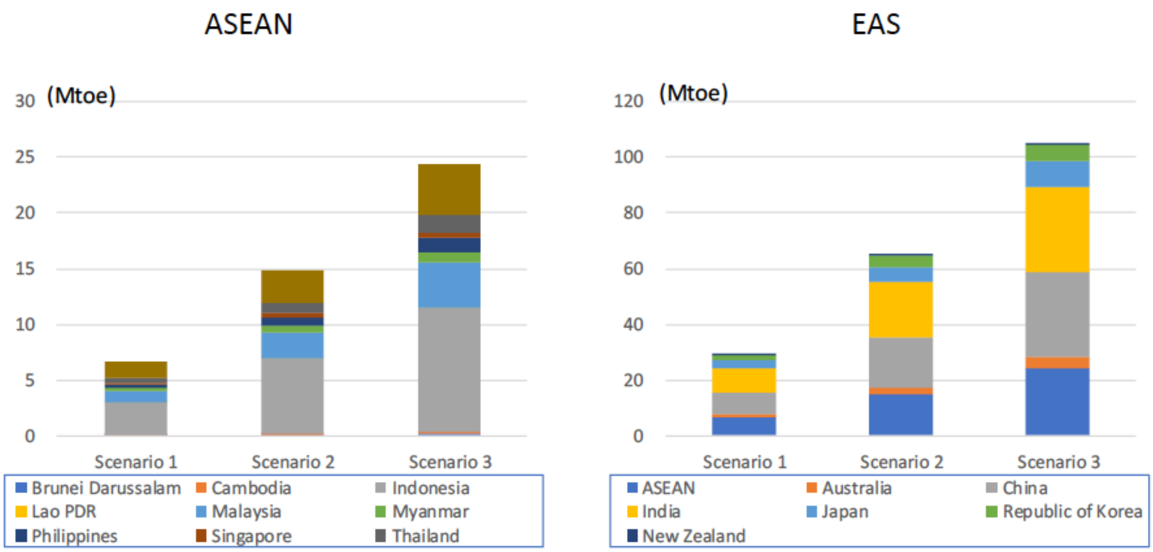
(iii) Hydrogen can be produced from clean and indigenous sources such as renewables, nuclear energy, biomass, and biofuel. This is critically important for the energy security of countries highly reliant on imports of fossil fuels to power transport.

(iv) The scale and location of hydrogen production are highly flexible, especially in the cases of onsite electrolysis and onsite transformation using pipeline natural gas. Hydrogen can be stored by many means, centralised or distributed, and then delivered using existing infrastructure such as road and rail. An electrified transport system, however, is vulnerable if fully reliant on the power grid; blackouts, cyberattacks, or physical attacks could paralyse road transport.

(v) When the share of intermittent renewables is high, using surplus or abandoned renewables to produce hydrogen can not only balance the power grid but also offer an option to store energy when the weather is sunny (solar), windy (wind), or rainy (hydropower) and release it back to the power grid when needed.

The potential of hydrogen as an energy carrier and a complementary development for large-scale expansion of renewable energy in ASEAN and East Asian countries should, therefore, be studied. An ERIA (2019) report estimated the following outlook for hydrogen demand in ASEAN and East Asia Summit countries (Figure 1).

Figure 1. Hydrogen Demand Potential by Country in 2040



ASEAN = Association of Southeast Asian Nations, EAS = East Asia Summit, Lao PDR = Lao People's Democratic Republic, Mtoe = million tonnes of oil equivalent.
Source: ERIA (2019).

This study investigates the economics of using hydrogen to store renewable energy and subsequently consumed by downstream applications in ASEAN and East Asian countries.

For the power sector, the cost of storing and then delivering each kilowatt-hour of renewable energy, which includes the cost of producing hydrogen, transporting and storing hydrogen, and then converting it into electricity, is compared with alternatives such as batteries and pumped hydropower.

For transport sector, a well-to-wheel model is used to compare the cost of fuel cell electric vehicles (FCEVs) powered by hydrogen sourced from renewable energy sources (RESs) with the cost of battery electric vehicles (BEVs), plug-in hybrid vehicles (PHEVs), and conventional internal combustion engine vehicles (ICEVs).

To substantiate the desktop research, the study interviewed experts and visited sites to investigate existing and potential demonstration projects that apply such energy storage concepts, to identify lessons, experience, and key barriers given technology levels and supply chain costs.

Chapter 2 reviews the literature on relevant topics. Chapter 3 discusses quantitative studies on the economics of using hydrogen to store renewable energy and the well-to-wheel model to assess the cost of FCEVs in ASEAN and East Asian countries. Chapter 4 summarises the findings from visits to demonstration projects in China and Japan. Chapter 5 concludes with policy implications.

Chapter 2

Literature Review

This section explores the economic feasibility of hydrogen as an energy carrier, based on the review of the academic literature. The study (i) summarises the prospects of hydrogen produced from RESs as an energy carrier, (ii) examines the feasibility of using RESs and hydrogen in remote locations such as islands, and (iii) reviews the potential of using hydrogen for FCEVs.

1. Hydrogen as Storage for Renewable Energy in the Power Sector

Renewable energy is becoming a key component in the energy mix to meet increasing electricity demand and reduce GHG emissions. Renewable energy's expansion, however, is limited by intermittency and peak-hour mismatch. Energy storage technologies must be developed to ensure that renewable energy is fully absorbed by the energy system. We review the economic feasibility of hydrogen storage for electricity produced from RESs.

Academic studies are divided on the profitability of hydrogen storage for RESs. Many studies stress that hydrogen storage is still far more expensive than fossil fuels and demands a lot of upfront investment. Hydrogen storage might not, therefore, be profitable in the end. APERC (2018) shows that producing hydrogen from RESs (US$0.22–US$0.55 cents/normal cubic metre [Nm^3]) is twice as costly as producing it from fossil fuels and carbon capture storage (CCS) (US$0.07–US$0.23/Nm^3).

Nagashima (2018) estimates that hydrogen produced in Japan from renewables is not competitive because of their high cost. The intermittency of renewables decreases the capacity factor of electrolysis and raises the marginal costs of hydrogen production. Hydrogen produced from RESs, therefore, remains more expensive than hydrogen made from natural gas and CCS, and hydropower.

Combining wind power and a hydrogen storage system for power plants is deemed economically unviable, as a mixed system of wind–hydrogen would increase investment costs in infrastructure components and significantly decrease profits (Loisel et al., 2015). Besides, the benefits of energy storage for hybrid wind–hydrogen power plants are limited by the decrease in overall efficiency. Therefore, hydrogen production costs from wind-powered electrolysis are higher than those of steam methane reforming (SMR) and SMR with CCS (Olateju et al., 2016). Eypasch et al. (2017) advised industrial power plants to convert excess energy to heat, rather than store it using liquid organic hydrogen carriers (LOHCs).

Other studies, however, indicate that hydrogen is an economically viable way to store hydrogen produced from RESs. Seyyedeh-Barhagh et al. (2019) attempted to satisfy economic and environmental conditions in optimising the performance of hydrogen storage systems, and prove that it is feasible to have an environmentally friendly and profitable hydrogen storage system that meets demand. However, these studies usually consider off-grid systems. Some conclude that the most beneficial configuration of offshore wind farms with hydrogen systems is to sell hydrogen directly to users, if there is enough demand for it (Hou et al., 2017). Favourable returns on investment are demonstrated by Hou et al. (2017) and Khosravi et al. (2018). Hydrogen has been proven to be highly profitable in the long term and exceedingly well suited for remote areas that are not connected to the national power grid (Khosravi et al., 2018). Prasanna and Dorer (2017) found similar results and argue that it is more profitable to produce hydrogen from excess RESs and use it within the district of production rather than sell it to the power grid. Yan et al. (2017) proved that hydrogen storage is an efficient, environmentally friendly, and profitable way to solve the issue of energy curtailment for renewables.

Assessing the economic feasibility of hydrogen storage remains complicated because the price range of hydrogen is large, since hydrogen demand profiles vary and storage technologies are not mature (APERC, 2018; Menanteau et al., 2011). Research is ongoing to figure out which storage technology is cheapest and most efficient and has the lowest level of loss (Di Profio et al., 2009; Teichmann et al., 2012; Reuß et al., 2017; Aako-Saksa et al., 2018; Abe et al., 2019). Studies point out that the most viable storage technologies are LOHC (Teichmann et al., 2012; Reuß et al., 2017; Aako-Saksa et al., 2018), circular hydrogen carriers (Aako-Saksa et al., 2018), and metal hydrides (Abe et al., 2019).

2. Hydrogen Use in Remote Island Locations

Here we review the possibilities of developing hydrogen use in remote islands, where, as many authors have shown, energy is a challenge (Young et al., 2007; Groppi et al., 2018; Dorotić et al., 2019). Many islands rely completely on fossil fuels (Dorotić et al., 2019). However, growing climate change concerns and the increasing profitability of renewables has helped increase the share of RESs. Yet, many issues remain, such as the intermittency or seasonality of energy production and demand mismatch in peak hours (Groppi et al., 2018; Cabrera et al., 2018). Several islands have started to see hydrogen as a solution.

One possibility is importing and distributing hydrogen produced from RESs, but several studies show that it is not economically viable. Teichmann et al. (2012) mentioned that, although long-distance liquid hydrogen (LH_2) transport by sea could be important in the future, it is not attractive now because of the low weight percentage and not feasible using existing ships. Because of its diesel-like properties, LOHC could be a storage solution. Whilst LOHC costs decrease spectacularly for short distances, they remain high for distances above 5,000 km, with 1 kg of hydrogen costing about €0.221. More recent studies emphasise that pipelines and short-distance delivery by truck are the preferred transport choices for hydrogen (Singh et al., 2015). Whilst ships allow for international transport of extremely high volumes of hydrogen, the price is prohibitive: US$1.80–US$2.00/kg compared with US$0.10–US$1.00 by pipeline (Singh et al., 2015). Boil-off losses of hydrogen are more significant when LH_2 technology is used (Singh et al., 2015). Overall, electricity transmission is far more efficient and the cheapest option for transporting energy. However, electrical energy is difficult to store and chemical energy such as hydrogen is inevitably the complementary solution (Teichmann et al., 2012).

Another possibility is producing electricity from RESs such as solar photovoltaic or wind, and using hydrogen storage and FCEVs to compensate for seasonality and to match energy demand in peak hours. Many islands have attempted to stop relying on fossil fuels and increase their renewable energy share. Chen et al. (2007) introduced programmes and trials of integrated fuel cells and hydrogen storage in various islands in Europe and concluded that 100% renewable energy penetration was technically and economically feasible for small islands. Ma et al. (2014) presented a feasibility study of a stand-alone hybrid solar–wind system with battery energy storage for a remote island of Hong Kong SAR, and showed that it could fully rely on RESs thanks to 'practical and cost-effective' battery storage. Several recent case studies have demonstrated that Mediterranean islands could use hydrogen storage and FCEVs to decrease their fossil fuel consumption (Groppi et al., 2018; Cabrera et al., 2018). Certain islands, such as Korčula in Croatia, could even rely entirely on RESs thanks to hydrogen storage technology (Dorotić et al., 2019). However, all the studies used examples of remote locations in developed countries that have national and regional energy and environmental legislation favouring hydrogen development (Chen et al., 2007). The feasibility of such trials in developing countries remains to be explored.

3. Hydrogen Produced from Renewable Energy Sources to Supply Fuel Cell Electric Vehicles

This section examines the economic feasibility of using hydrogen produced from RESs to supply FCEVs. Climate change concerns and the willingness to decrease GHG emissions from transport required considering hydrogen as a potential transport fuel. The transition to hydrogen fuel would offer social benefits, including greater energy security, reduced pollution, and a drop in GHG emissions (Southall and Khare, 2016). However, the development of renewables-produced hydrogen for fuel cell applications has been slow.

The first obstacle to its development is what many authors call the 'chicken and egg dilemma' (Southall and Khare, 2016; Campinez-Romero et al., 2018). Campínez-Romero et al. (2018) argued that the main reason for the lack of FCEV adoption is the lack of a hydrogen refuelling network, contributing to low demand for FCEVs. However, to develop hydrogen refuelling stations (HRSs), they must be fundable and economically viable, which they are not because of low demand. Southall and Khare (2016) argued that, despite the existence of commercial-scale hydrogen production, the distribution network depends on the sale of hydrogen-fuelled vehicles.

Another obstacle is the high costs of HRSs, as highlighted by several studies (Frank et al. 2019; Apostolou and Xydis, 2019; Bai and Zhang, 2020). Inadequate deployment of HRSs is a major barrier to the commercial introduction of FCEVs. Investments in HRSs would be profitable if FCEV numbers grew, but the FCEV market would be hindered if hydrogen infrastructure development were inadequate (Apostolou and Xydis, 2019).

Xu et al. (2020) recognised six barriers to developing HRSs in China, where HRS construction is lagging behind expectations: high initial capital cost (B11), limited financing channels (B13), immature hydrogen storage technology (B22), incomplete hydrogen transportation technology (B23), lack of standards (B42), and an imperfect subsidy mechanism (B43). A ranking of the relative importance of these barriers is concluded in the case of China.

How can HRSs be financed and operated? Bai and Zhang (2020) introduced four business models for financing and operating HRSs (build-operate-transfer, transfer-operate-transfer, public–private partnership, and asset-backed securitisation) and identified six criteria for prioritising them.

Taghizadeh-Hesary and Yoshino (2019, 2020) found that lack of long-term financing, low rate of return, existence of various risks, and market players' lack of capacity are major challenges to developing green energy projects, including hydrogen projects. The authors provide practical solutions for filling the green financing gap, including increasing the role of public financial institutions and non-banking financial institutions (pension funds and insurance companies) in green investments, utilising the spillover tax to increase the rate of return of green projects, developing green credit guarantee schemes to reduce credit risk, establishing community-based trust funds, and mitigating green investment risks via financial and policy de-risking.

Another reason for the lack of HRS infrastructure is the high upfront investment needed to build it. Nagashima (2018) argued that, particularly in Japan, despite heavy subsidies to develop FCEVs, tight regulations and technical constraints raise infrastructure costs: an HRS costs two or three times more than in Europe. However, some authors argue that lack of infrastructure and financial resources used to be an issue at the beginning of the commercialisation of fossil fuels, as well (Singh et al., 2015). Therefore, it can be overcome with support from government and state subsidies (Campinez-Romero et al., 2018). Subsidies would significantly reduce the costs of hydrogen technologies (Nistor et al., 2016) and increase the share of RES-produced hydrogen (Southall and Khare, 2016).

Most studies that assess the economic feasibility of hydrogen use for FCEVs conclude that costs could be brought down through subsidies and economies of scale of electrolysers and hydrogen storage equipment (Southall and Khare, 2016; Kan and Shibata, 2018). Nistor et al. (2016) argued that the hydrogen unit cost could be below that of petrol if the expected return on investment period were over 10 years for proton exchange membrane (PEM) and electrolysers and 5 years for alkaline electrolysers. Whilst hydrogen technologies seem to be profitable in the long term, Southall and Khare (2016) argued that, in the short term, hydrogen production infrastructure, coupled with renewable energy tariffs, would be financially viable under certain configurations.[1]

4. Summary of the Literature Review

We reviewed the academic literature to analyse the economic feasibility of RES-produced hydrogen storage for power generation and FCEVs and for remote locations. It appears that hydrogen produced from RESs is not competitive with that produced from fossil fuels. However, hydrogen storage proves to be a desirable way to increase electricity produced from RESs and solve curtailment issues. Uncertainty remains, however, over economic feasibility as the price range for hydrogen is large and technology is still not mature.

The cost of hydrogen transport and distribution proves to be a substantial portion of the overall supply cost of hydrogen. The literature shows that long-distance transport of hydrogen to remote locations is not economically feasible now. However, hydrogen is an economically feasible solution for remote islands to store RES-produced electricity and, in certain cases, can meet all energy demand. In both cases, state subsidies would not only help overcome issues of high upfront investment in infrastructure development but also resolve the chicken-and-egg dilemma.

Incentivising projects for private investors through green credit guarantee schemes, utilising the spillover effect of power supply, and mitigating green investment risks via financial and policy de-risking are recommended.

[1] The authors used average wind speeds in the United Kingdom for their calculations. Varying wind speed might affect the results of the study.

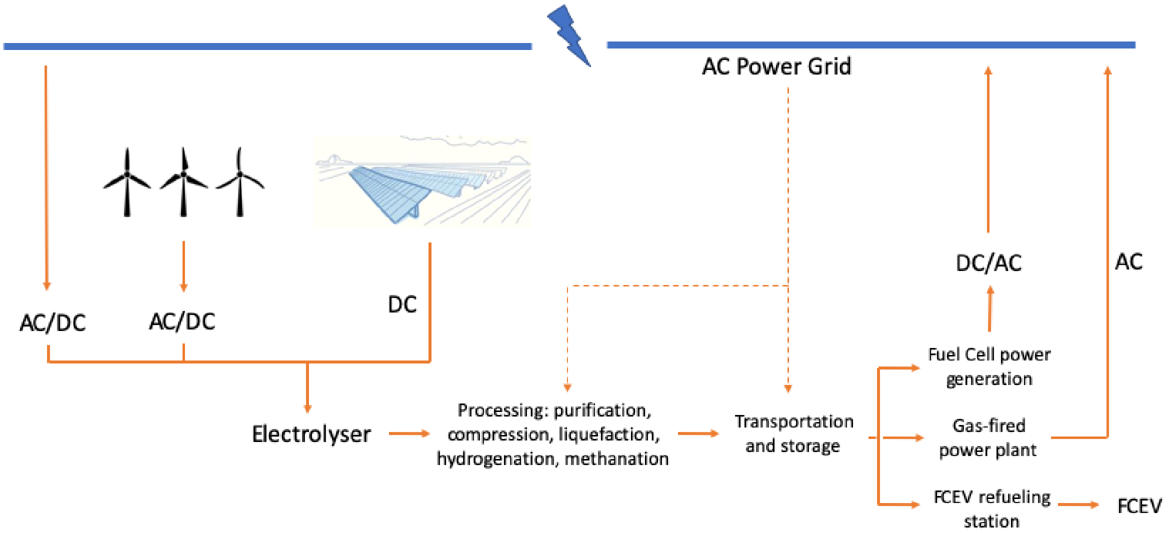
Chapter 3

Quantitative Methodologies and Results

1. Model Concept

This section investigates energy consumption and the economic costs of hydrogen as an energy storage solution for renewable energy in ASEAN and East Asian countries. First, the cost of storing and delivering each kilowatt-hour of renewable energy, including the cost of producing hydrogen, logistics costs of transporting and storing hydrogen, and the cost of converting hydrogen into electricity, will be compared with alternative pathways such as batteries and pumped hydropower. Our model can simulate energy storage on a daily, weekly, and even monthly basis (Figure 2).

Figure 2: Concept of Renewables-to-Hydrogen Energy System



AC = alternating current, DC = direct current, FCEV = fuel cell electric vehicle.
Source: Authors.

Second, for transport applications, a well-to-wheel model is used to compare the cost of producing and delivering hydrogen from RESs and powering FCEVs with the cost of fuel for alternative powertrains such as BEVs, PHEVs, and conventional ICEVs. In the simulation scenarios that follow, we model and simulate a hydrogen supply chain that stores energy weekly.

2. Renewable Energy to Hydrogen: Production, Transport, and Distribution

The study focuses on renewable energy storage using hydrogen. For final use application, the system is extended into power applications to regenerate electricity and supply the power grid, and into transport applications to supply fuel to FCEVs. The key components of such a system are shown in Figure 3.

Figure 3. Key Components of a Renewables-to-Hydrogen Energy System

Production

1	AC/DC Converter
2	Electrolyser
3	Purification

Transportation, Storage and Delivery

	Pipeline	Compressed Gaseous	Liquid	LOHC
1	Compressor	Compressor	Liquefaction	LOHC Hydrogenation
2	Gaseous Storage	Gaseous Ship/Tube Trailer Truck	Liquid Ship/Tube Trailer Truck	Organic Hydride (LOHC) Ship/Truck
3	Pipeline	Gaseous Storage	Liquid H2 Storage Tank	LOHC Dehydrogenation
4	Gaseous Refilling Station	Gaseous Refilling Station	Liquid Pump	Compressor
5			Liquid Refilling Station	Gaseous Refilling Station

Gas to Power

	Fuel Cell	Gas Turbine
1	Fuel Cell Stack	Gas Turbine
2	DC/AC Converter	

FCEV Applications

Passenger Car
Bus
Truck

AC = alternating current, DC = direct current, FCEV = fuel cell electric vehicle, LOHC = liquid organic hydrogen carrier.
Source: Authors.

The production of hydrogen starts with an AC-to-DC converter, followed by an electrolyser. Our model covers two types of electrolyser – alkaline and PEM – and distinguishes between a 50-kilowatt (kW) small unit and a 1,000 kW large unit. Once hydrogen is produced through electrolysis, it is purified to at least 99.7% of gas content.

At the transport, storage, and delivery stages, we face many options. This study covers four major pathways: pipeline, compressed gaseous, liquefied, and organic hydride (LOHC). Each pathway consists of the following:

(i) Pipeline: compressor (100 bar), gaseous storage, pipeline, and gaseous compressed HRS (950 bar)

(ii) Compressed hydrogen: compressor (550 bar), compressed hydrogen ship or tube trailer truck, compressed hydrogen storage, and gaseous compressed HRS (950 bar)

(iii) Liquid hydrogen (LH_2): liquefaction, liquid hydrogen ship or tube trailer truck, liquid hydrogen storage tank, liquid pump, and liquid HRS

(iv) Organic hydride (LOHC): LOHC hydrogenation, LOHC ship or truck, LOHC dehydrogenation, compressor, and gaseous compressed HRS (950 bar)

The delivered hydrogen ends up in power and transport. In the case of power, hydrogen is returned into electricity and injected into the power grid by two pathways: fuel cell and gas turbine. In the case of the fuel cell pathway, our model includes PEM, solid oxide fuel cells, and molten carbonate fuel cells, with small (5 kilowatt-electric [kWe]) to large (1.4 megawatt-electric [MWe]) capacities optional. In the case of a gas turbine, hydrogen is mixed with natural gas and combusted for power generation.

In the case of road transport, fuel cell passenger cars, buses, and trucks are compared with alternative powertrains such as BEVs, PHEVs, and conventional ICEVs. A well-to-wheel and total cost of ownership (TCO) model is applied, considering hydrogen sourced from renewables and taking the cost of delivered hydrogen as input from the model.

Since we consider hydrogen as energy storage for renewables, our model starts with assumptions for a renewable energy project. Table 1 shows an example of the specifications for modelling. By assuming a ratio of curtailment of renewable electricity, because of its intermittency, we can get the total amount of energy to be converted into hydrogen. Capacity can be chosen in our model from 1 MWe to 4,000 MWe in simulating other scenarios with different scales of projects.

Table 1. Specifications of a Renewable Energy Project: An Example

Renewable Type	Solar PV	
Capacity (MW)	1,000	MWe
Curtailment	25%	
Annual generation	1,752,000	MWh
Curtailed energy	438,000	MWh

MW = megawatt, MWe = megawatt-electric,
Source: Authors.

The annual generation for different types of renewable technologies is based on the following assumptions (Table 2).

Table 2. Capacity Factor of Renewable Energy Technologies

	Capacity Factor
Solar photovoltaic	20%
Wind	33%
Hydro	36%
Biomass	50%
Geothermal	48%

Source: Authors.

Table 3 lists the CAPEX and OPEX assumptions of the key components of the supply system.

Table 3. Capital Expenditure and Operational Expense Assumptions of Key Components of Supply

Component	CAPEX	OPEX (% of CAPEX p.a.)	Life	Energy Consumption
Large alkaline electrolyser	\$1,102/kWe	4.7	140,000 hours	3.98 kWh/m^3
Large PEM electrolyser	\$1,808/kWe	4.6	140,000 hours	3.48 kWh/m^3
Hydrogen pipeline	\$399,799/km	8%	50 years	
Tube trailer terminal compressor	\$260/kg H_2/day	10%	15 years	1.1 kWh/kg
Liquefaction plant	\$1,867/kg H_2/day	3.6%	30 years	12 kWh/kg
Hydrogenation plant	\$2,104/kg H_2/day	4%	20 years	0.37 kWh/kg
Gaseous geological storage	\$226/kg H_2	1.5%	40 years	
CH_2 storage tank	\$1,100/kg H_2	1.5%	30 years	
LH_2 storage tank	\$27/kg H_2	1%	30 years	
Gaseous tube trailer truck	\$1,015/kg H_2	11.33%	15 years	0.0004 litre/km/kg (diesel)
Liquid tube trailer truck	\$295/kg H_2	3.5%	13 years	0.0004 litre/km/kg (diesel)
LOHC truck	\$189/kg H_2	2%	20 years	0.0002 litre/km/kg (diesel)
LH_2 ship	\$1.1/kg H_2	11%	20 years	0.0012 litre/km/kg (diesel)
LOHC ship	\$31,479/kg H_2	12%	20 years	0.000001 kg/km/kg (HFO)

CH_2 refuelling station	\$13,637/kg H_2/day	5.5%	15 years	4.67 kWh/kg
LH_2 refuelling station	\$1,712/kg H_2/day	2.6%	10 years	0.17 kWh/kg
PEMFC power station	\$20,792/kWe	0.9%	11,000 hours	19.2 kWh/kg
SOFC power station	\$18,645/kWe	0.7%	50,000 hours	13.4 kWh/kg

CH_2 = compressed hydrogen, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier, PEM = proton exchange membrane, PEMFC = PEM fuel cell, SOFC = solid oxide fuel cell.
Source: Authors, based on experts' estimates.

Table 4 lists the different transport and delivery scenarios, with varying distances assumed.

Table 4. Transport and Delivery Scenarios

	Distance (km)
Domestic onsite	0
Domestic medium distance	100
Domestic long distance	500
Overseas long distance	2000

km = kilometre.
Source: Authors.

Table 5 presents our assumptions on energy costs in each ASEAN and East Asian country covered in this study. The cost of grid electricity is a necessary input to our model, as the supply chain of hydrogen is long and various components inevitably need to access grid power for their sustained functioning.

Table 5. Energy Cost Assumptions

Country	Grid Electricity (US\$/kWh)	SPV (US\$/kWh)	Wind (US\$/kWh)	Hydropower (US\$/kWh)	Biomass (US\$/kWh)	Geothermal (US\$/kWh)	Diesel (US\$/litre)	Gasoline Cost (US\$/litre)	Heavy Fuel (US\$/metric tonne)
Australia	0.095	0.038	0.049	0.034	0.106	0.0362	1	0.98	455.5
China	0.092	0.029	0.044	0.033	0.106	0.0362	0.9	1.01	455.5
Indonesia	0.082	0.04	0.04	0.033	0.106	0.0362	0.86	0.71	455.5
Japan	0.111	0.058	0.066	0.0563	0.106	0.0362	1.12	1.29	455.5
Republic of Korea	0.046	0.07	0.085	0.0563	0.106	0.0362	1.16	1.29	455.5
India	0.1	0.029	0.04	0.033	0.106	0.0362	0.98	1.08	455.5
Malaysia	0.087	0.04	0.04	0.033	0.106	0.0362	0.52	0.5	455.5
New Zealand	0.087	0.038	0.051	0.034	0.106	0.0362	1.02	1.53	455.5
Russia	0.02	0.029	0.044	0.055	0.106	0.0362	0.71	0.71	455.5
Thailand	0.068	0.038	0.04	0.033	0.106	0.0362	0.86	1.17	455.5
United States	0.068	0.03	0.05	0.0563	0.106	0.0362	0.8	0.79	455.5
Viet Nam	0.086	0.041	0.057	0.033	0.106	0.0362	0.71	0.88	455.5

kWh = kilowatt-hour, SPV = solar photovoltaic.
Source: Authors.

In each scenario of the hydrogen supply chain, factors such as host country, source of energy, project capacity, electrolyser type, and specification of the transport and delivery pathway could all be specified from a list of technical options (Figure 4, Figure 5).

Figure 4. Specification of Hydrogen Supply Chain as Storage of Renewable Electricity: An Example

Country	Source of RE	RE Capacity (kW)	Electrolyser	System Utilisation Rate	Transport	Transport Scenario	Storage	Duration of Storage (days)	FC Power Generation	Power Generation
Republic of Korea	SPV	4000000	Alkaline	80%	Pipeline	Overseas long distance	Yes	7	SOFC CHP (1.4MWe, 1.1MWt)	Fuel cell

RE = renewable energy, LOHC = liquid organic hydrogen carrier, PEM = proton exchange membrane, RE = renewable energy, SPV = solar photovoltaic.
Source: Authors.

Figure 5. Specification of Hydrogen Supply Chain for Delivery at Refuelling Stations: An Example

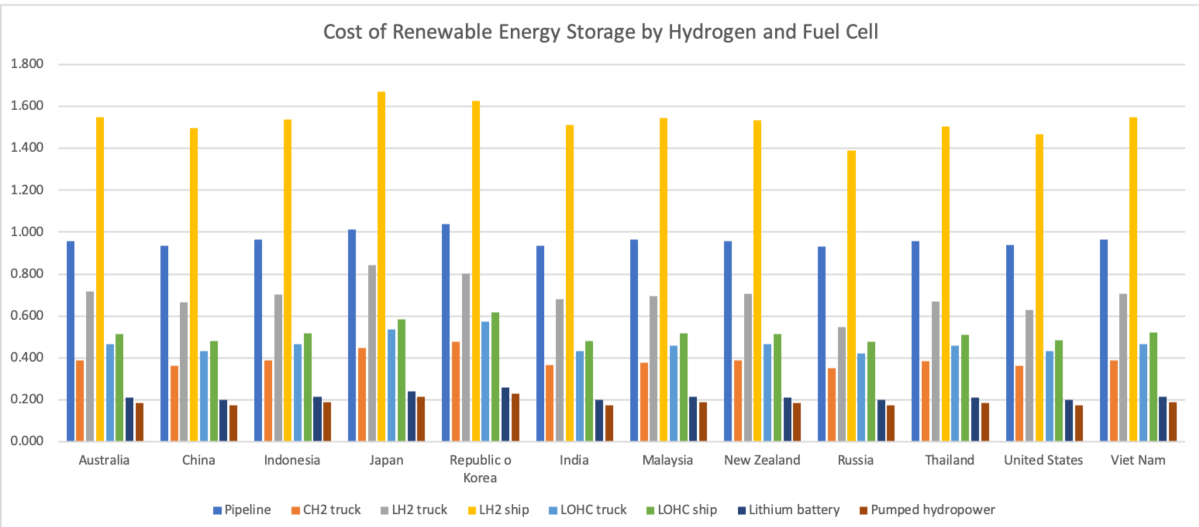
Country	Source of RE	RE Capacity (kW)	Electrolyser	System Utilisation Rate / Capacity Factor	Transport	Transport Scenario	Storage	Refilling Station	Duration of Storage (days)	Storage Means
China	SPV	4000000	PEM	80%	LOHC truck	Domestic medium distance	Yes	Small	7	Gaseous geological storage (Pressurized tank <100 bar)

RE = renewable energy, CHP = combined heat and power, FC = fuel cell, LOHC = liquid organic hydrogen carrier, SOFC = solid oxide fuel cell, MWt = megawatt thermal, MWe = megawatt-electrical, SPV = solar photovoltaic.
Source: Authors.

3. Power Applications

We present the results of cross-country comparisons for each type of renewable energy and consider the case of a renewable energy project with 1,000 megawatts (MW) of capacity. Figure 6 presents the cost of renewable energy, solar PV in this case, stored as hydrogen and subsequently converted into electricity by fuel cell. The transport scenario considered is 'overseas long distance', with 7 days of storage capacity in each supply pathway.

Figure 6. Cost of Storing Solar Energy as Hydrogen and Generating Electricity Using Fuel Cell ($/kWh)



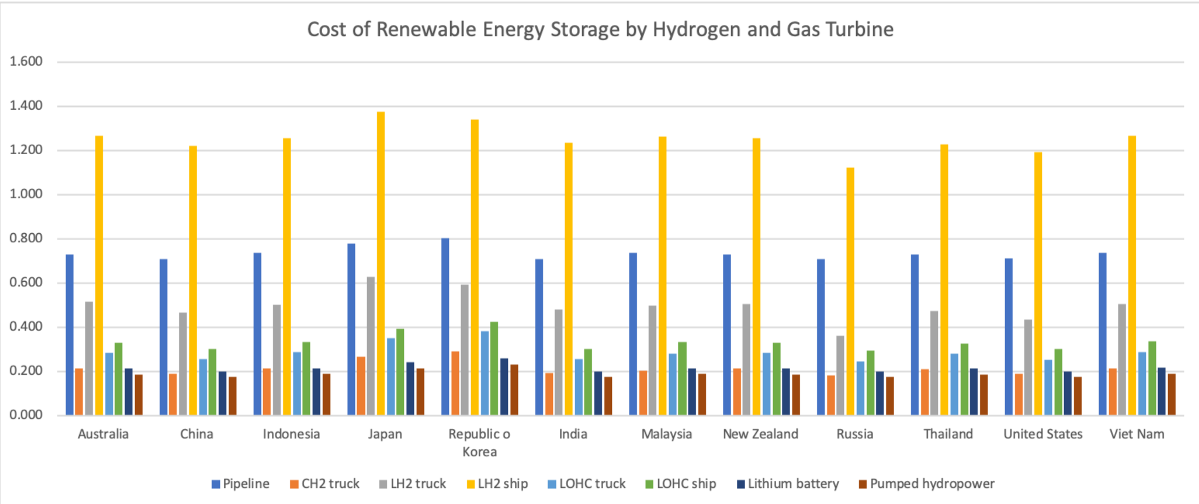
CH_2 = compressed hydrogen, kWh = kilowatt-hour, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

Renewable energy storage and transport by ship as liquid hydrogen is the most expensive, followed by the pipeline pathway. Both pathways have high CAPEX. Hydrogen transported by compressed-hydrogen truck is the cheapest of all hydrogen supply pathways. However, it is still about twice as expensive as renewable energy stored in lithium batteries and pumped hydropower.

In estimating the cost of electricity stored and then delivered in lithium batteries and pumped hydropower, for the exact number of days and over the same transmission distance as specified in each scenario, our model accounts for energy losses, transmission losses, and costs of transmission.

Figure 7 presents the cost of renewable energy, solar PV in this case, stored as hydrogen and then converted into electricity by gas turbine. The transport scenario considered is also 'overseas long distance'. Since gas turbines have much lower CAPEX than fuel cells, the cost of electricity from hydrogen pathways is much lower than in Figure 6. The cost of electricity in the compressed-hydrogen truck pathway is close to competitive against energy storage by lithium battery.

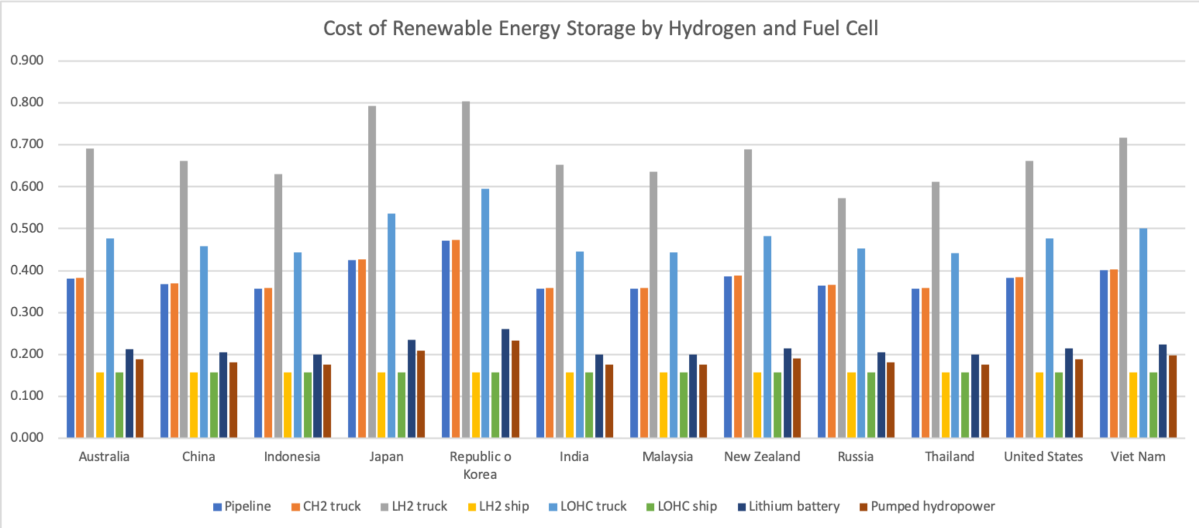
Figure 7: Cost of Storing Solar Energy as Hydrogen and Generating Electricity Using Gas Turbine (US$/kWh)



CH_2 = compressed hydrogen, kWh = kilowatt-hour, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

The next two scenarios have wind energy stored by hydrogen, considering 'domestic medium distance' transport and delivery, also with 7 days of storage. Figure 8 represents fuel cell application and Figure 9 gas turbine.

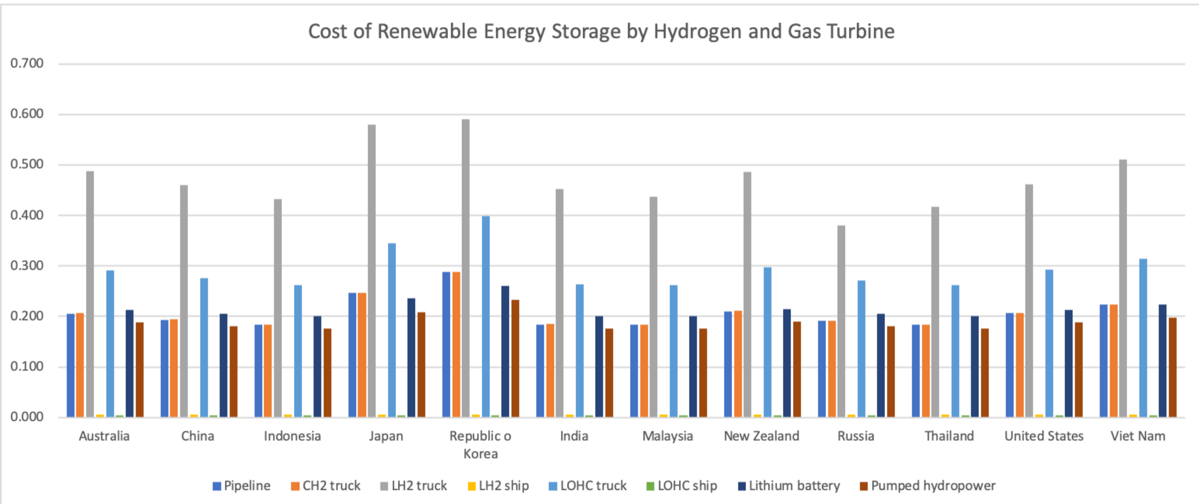
Figure 8. Cost of Storing Wind Energy as Hydrogen and Generating Electricity Using Fuel Cell (US$/kWh)



CH_2 = compressed hydrogen, kWh = kilowatt-hour, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

In a 'domestic medium-distance' scenario shipping pathways are no longer applicable (Figure 8). Liquefied-hydrogen truck is the most expensive since the CAPEX of liquefaction is high. It is followed by LOHC truck. Pipeline and compressed-hydrogen pathways are the cheapest of all hydrogen pathways but still significantly higher than lithium battery and pumped hydropower storage.

Figure 9. Cost of Storing Wind Energy as Hydrogen and Generating Electricity Using Gas Turbine (US$/kWh)

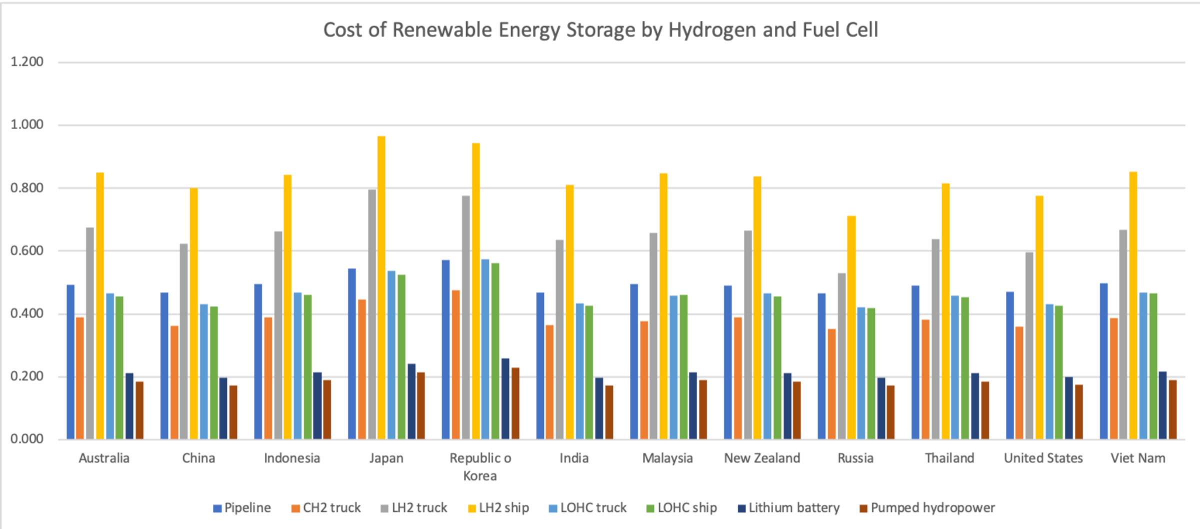


CH_2 = compressed hydrogen, kWh = kilowatt-hour, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

Figure 9 shows that, in returning hydrogen into electricity by gas turbine, the cost of stored electricity could even compete with lithium battery storage in the case of pipeline and compressed-hydrogen truck for transport and delivery.

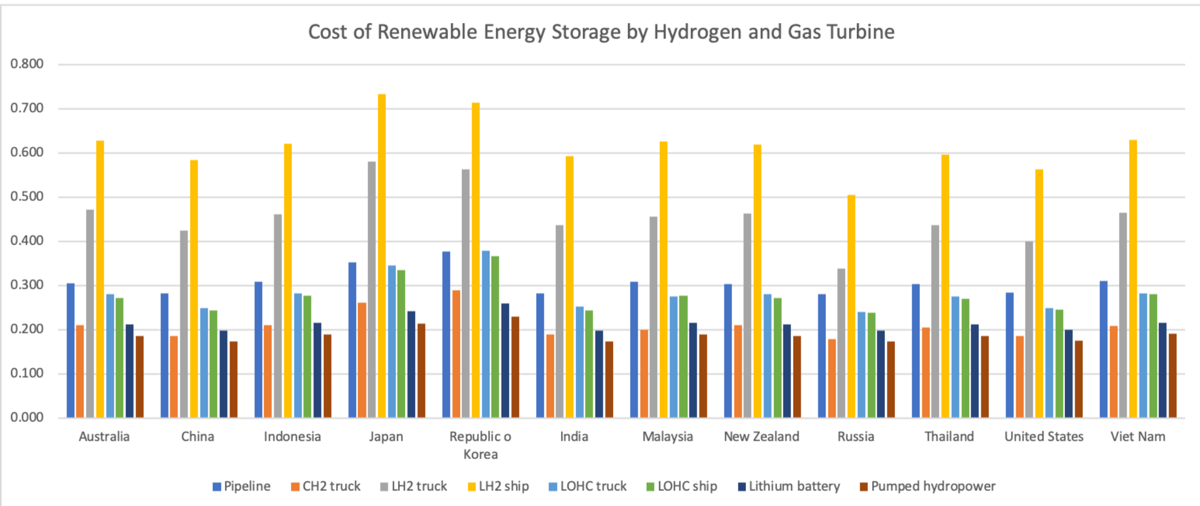
Further experiments with our model show that the hydrogen supply chain has significant economies of scale, which would lower the delivered cost per kilowatt-hour of stored energy if, say, we increased RESs to 4,000 MW. Figure 10 and Figure 11 present such economy of scale for solar as the source of energy in a 'overseas long-distance' scenario, with 7 days of storage.

Figure 10. Cost of Storing Solar Energy as Hydrogen and Generating Electricity Using Fuel Cell ($/kWh)



CH_2 = compressed hydrogen, kWh = kilowatt-hour, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

Figure 11. Cost of Storing Solar Energy as Hydrogen and Generating Electricity Using Gas Turbine (US$/kWh)



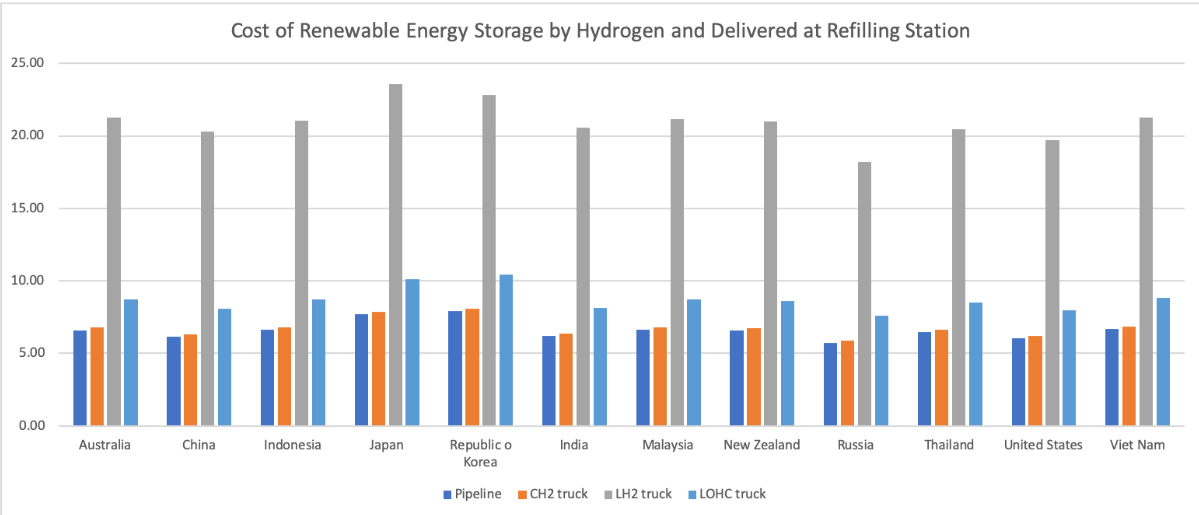
CH_2 = compressed hydrogen, kWh = kilowatt-hour, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

As can be observed from Figure 10 and Figure 11, compared with Figure 6 and Figure 7, the economies of scale of solar-based pathways are evident despite the longer transport distance, especially for the liquefied and pipeline pathways, which are more capital-intensive than others. The cost of renewable energy stored by compressed gaseous hydrogen using gas turbine can beat that of lithium battery in most countries.

4. Transport Applications

In transport, the first step is to deliver hydrogen at the refuelling station. Figure 12 presents the cost of producing hydrogen using renewable energy (1,000 MW) and supplying hydrogen to refill FCEVs at a medium distance in the domestic market, with 7 days of storage.

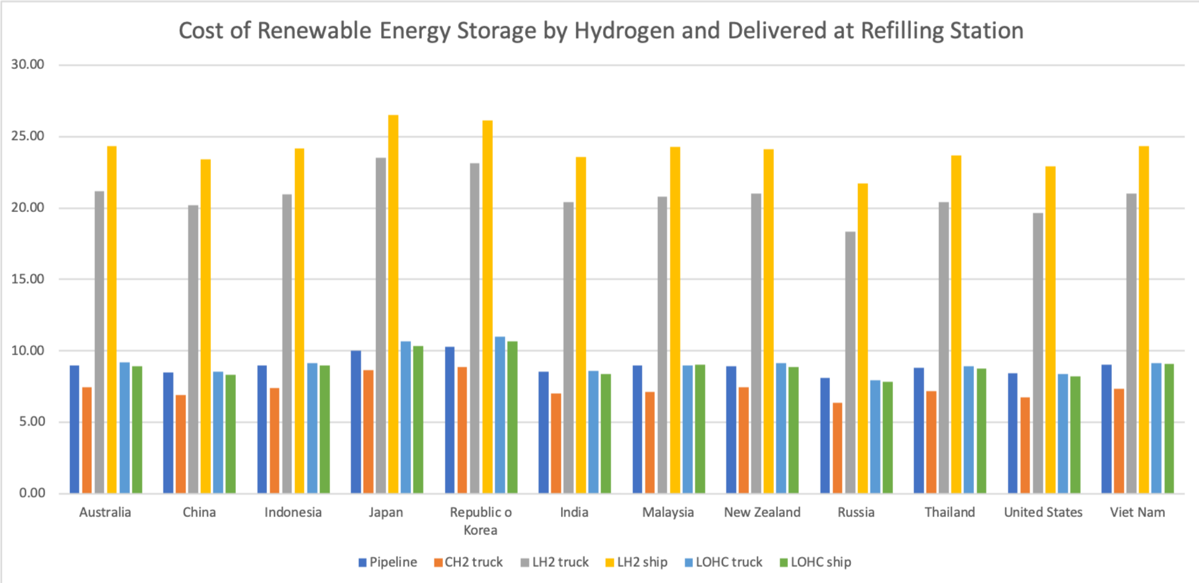
Figure 12. Cost of Storing Solar Energy as Hydrogen and Delivered at Refuelling Station (domestic medium distance) (US$/kg)



CH_2 = compressed hydrogen, kg = kilogram, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

Such can be compared with the case of 'overseas long-distance' supply, with solar PV capacity of 4,000 MW, where we have two more options for the supply pathway by shipping (Figure 13).

Figure 13. Cost of Storing Solar Energy as Hydrogen and Delivered at Refuelling Station (overseas long distance) (US$/kg)



CH_2 = compressed hydrogen, kg = kilogram, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

In the following, we apply the results of the above modelling (the cost of hydrogen delivered at refuelling stations) to the FCEV TCO model and compare it with the cost of owning and using vehicles based on alternative powertrains such as BEVs, PHEVs, and conventional ICEVs.

We consider the scenario of solar PV as an energy source for hydrogen production with domestic medium-distance transport and delivery, at a renewable energy capacity of 1,000 MW, with 7 days of storage. Table 6–Table 13 present the TCO in US dollars per kilometre by various vehicle fleets in Australia, China, Japan, the Republic of Korea, India, New Zealand, Russia, and the US, respectively.

Table 6. Total Cost of Ownership of Fuel Cell Electric Vehicles in Different Fleets Fuelled with Hydrogen from Solar Energy in Australia (US$/km)

H_2 Pathway	FCEV Fleet		
	Passenger Car	Bus	Truck
Pipeline	0.540	3.234	3.107
CH_2 truck	0.543	3.258	3.139
LH_2 truck	0.732	5.176	5.681
LOHC truck	0.568	3.512	3.475

CH_2 = compressed hydrogen, FCEV = fuel cell electric vehicle, H_2 = hydrogen, km = kilometre, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

Table 7. Total Cost of Ownership of Fuel Cell Electric Vehicles in Different Fleets Fuelled with Hydrogen from Solar Energy in China (US$/km)

H_2 Pathway\FCEV Fleet	Passenger Car	Bus	Truck
Pipeline	0.301	3.556	3.163
CH_2 truck	0.304	3.580	3.195
LH_2 truck	0.490	5.461	5.689
LOHC truck	0.327	3.817	3.510

CH_2 = compressed hydrogen, FCEV = fuel cell electric vehicle, H_2 = hydrogen, km = kilometre, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

Table 8. Total Cost of Ownership of Fuel Cell Electric Vehicles in Different Fleets Fuelled with Hydrogen from Solar Energy in Japan (US$/km)

H_2 Pathway\FCEV Fleet	Passenger Car	Bus	Truck
Pipeline	0.588	3.275	3.259
CH_2 truck	0.590	3.298	3.289
LH_2 truck	0.784	5.253	5.881
LOHC truck	0.618	3.577	3.659

CH_2 = compressed hydrogen, FCEV = fuel cell electric vehicle, H_2 = hydrogen, km = kilometre, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

Table 9. Total Cost of Ownership of Fuel Cell Electric Vehicles in Different Fleets Fuelled with Hydrogen from Solar Energy in the Republic of Korea (US$/km)

H_2 Pathway\FCEV Fleet	Passenger Car	Bus	Truck
Pipeline	0.664	3.613	3.599
CH_2 truck	0.666	3.635	3.629
LH_2 truck	0.866	5.655	6.307
LOHC truck	0.699	3.960	4.060

CH_2 = compressed hydrogen, FCEV = fuel cell electric vehicle, H_2 = hydrogen, km = kilometre, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

Table 10. Total Cost of Ownership of Fuel Cell Electric Vehicles in Different Fleets Fuelled with Hydrogen from Solar Energy in New Zealand (US$/km)

H_2 Pathway\FCEV Fleet	Passenger Car	Bus	Truck
Pipeline	0.625	3.649	3.485
CH_2 truck	0.628	3.675	3.520
LH_2 truck	0.839	5.811	6.351
LOHC truck	0.656	3.960	3.898

CH_2 = compressed hydrogen, FCEV = fuel cell electric vehicle, H_2 = hydrogen, km = kilometre, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

Table 11. Total Cost of Ownership of Fuel Cell Electric Vehicles in Different Fleets Fuelled with Hydrogen from Solar Energy in Russia (US$/km)

H_2 Pathway\FCEV Fleet	Passenger Car	Bus	Truck
Pipeline	0.668	3.664	3.411
CH_2 truck	0.670	3.686	3.441
LH_2 truck	0.850	5.504	5.851
LOHC truck	0.695	3.937	3.774

CH_2 = compressed hydrogen, FCEV = fuel cell electric vehicle, H_2 = hydrogen, km = kilometre, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

Table 12. Total Cost of Ownership of Fuel Cell Electric Vehicles in Different Fleets Fuelled with Hydrogen from Solar Energy in the United States (US$/km)

H_2 Pathway\FCEV Fleet	Passenger Car	Bus	Truck
Pipeline	0.631	3.456	3.621
CH_2 truck	0.633	3.477	3.649
LH_2 truck	0.802	5.186	5.914
LOHC truck	0.655	3.701	3.945

CH_2 = compressed hydrogen, FCEV = fuel cell electric vehicle, H_2 = hydrogen, km = kilometre, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

The TCO of FCEVs is compared with that of BEVs (US$0.40–US$0.50/km), PHEVs (US$0.30–US$0.40/km), and ICEVs (US$0.20–US$0.30/km) for passenger cars. For buses, the TCO of these alternative powertrains is typically in the range of US$1.50–US$1.80/km, and for trucks US$0.80–US$0.90/km. Therefore, except for FCEVs as passenger cars in China (where an exceptionally high level of subsidy is provided to purchase them), FCEVs coupled with hydrogen supplied from renewables are still not competitive against other powertrain technologies.

Such outcome is driven by the high cost of hydrogen supplied from RESs and the high CAPEX of FCEVs. If we compare the cost of hydrogen supplied at the refuelling stations (Figure 11, Figure 12) with the US$4.00/kg target, estimated as the competitive price by the US Department of Energy, current hydrogen supply costs should be reduced by about 50% or more, depending on the supply pathways. The CAPEX of FCEVs is at least three times higher than that of ICEVs.

Chapter 4

Main Findings of Interviews and Site Visits

To further substantiate the desktop research, we conducted interviews and visited sites to investigate the demonstration projects that apply hydrogen energy storage, to identify lessons, experience, and key barriers given the current levels of technologies and costs of supply chains.

Lessons from China

Sites visited in China were the Sichuan Energy Internet Research Institute, Tsinghua University in Chengdu, and Chengdu Lyuzhou Renewable Energy in Chengdu (Sichuan Province); and Energy China in Guangzhou, R&D Centre of Hydrogen Energy Standardization in Foshan, and Hydrogen Industrial Park and related infrastructure in Nanhai county, Foshan (Guangdong Province).

China could soon be one of the biggest producers and consumers of hydrogen energy. As of 2019, the central government had issued over 10 policy documents, and of 34 provincial administrative regions, 17, in addition to 22 municipalities, had issued policies to develop hydrogen energy-related industries and infrastructure.[2] Guangdong Province issued the most numbers of policies.

Guangdong Province provides the most generous subsidies for FCEVs and HRSs, in addition to central government subsidies. Table 13 summarises central and local subsidy policies as of 2019.

Table 13. Central and Local Subsidies for Fuel Cell Electric Vehicles in China, as of 2019

	Central Government	Guangdong Province
FC passenger vehicle	CNY6000/kW (up to CNY200,000 per vehicle)	CNY200,000 per vehicle
FC light truck or bus	CNY300,000 per vehicle	CNY300,000 per vehicle
FC heavy truck or bus	CNY500,000 per vehicle	CNY500,000 per vehicle
HRS		Up to CNY 8 million per station

CNY = yuan, FC = fuel cell, kW = kilowatt, HRS = hydrogen refuelling station.
Source: Authors, based on published reports.

[2] Source: Sohu.com news titled "Stock taking of policies on hydrogen fuel cell vehicles and hydrogen energy industries in the first half of 2019" (in Chinese) http://www.sohu.com/a/327206089_618917 (accessed 30 Dec 2019)

Over 2,000 FCEVs operate in China, mostly supported by demonstration projects, together with 26 HRSs.[3] The number of HRSs is expected to increase to 1,000 by 2030 (Author, Year).[4]

It was surprising, however, to find that most demonstration projects source hydrogen from conventional petroleum by-product hydrogen. All HRSs use compressed-hydrogen trucks to transport hydrogen at 35 MPa (350 bar). For these reasons, hydrogen energy is neither competitive in price (about CNY85/kg for refuelling at the HRS) nor green.

We understood from local experts that, besides the lack of economic competitiveness of the hydrogen supply chain, two main barriers stand in the way of developing green or clean hydrogen energy. First, comprehensive and valid feasibility studies are lacking on potential renewable or clean energy-to-hydrogen projects and their associated energy infrastructure network for transport and distribution.

Second, stakeholders have no consensus on who should do what to dismantle the institutional and regulatory barriers. For example, the power grid company has no redundant capacity to transmit the curtailed renewables or nuclear energy to a hydrogen production facility near the demand market. To build new transmission lines, decisions have to be approved by central regulation bodies. The power grid company, however, has no incentive to build dedicated new lines for such purpose, partly because of lack of understanding and partly because downstream market demand for hydrogen is not guaranteed. It is a 'chicken-and-egg' situation. Power regulations do not allow onsite production of hydrogen at renewable power stations, either, even if they were to use curtailed electricity.

An implementation plan study could collect information and ideas from experts in industry, government, and academia to identify economic and non-economic barriers, and determine who should do what by when. China needs a framework of policies that support clean and green hydrogen energy.

Like solar and wind power in the past 2 decades, hydrogen power technology will experience accelerated improvement and decline in cost because of the learning effect, economies of scale, and the network effect of hydrogen infrastructure, which are typical in the rise of new back-stop technologies. Policy support to get the industry through the typical 'Death Valley' of new technologies is critical.

Lessons from Japan

Because of the outbreak of the coronavirus disease (COVID-19), physical site visits were impossible within the project's time scope. Instead, we interviewed hydrogen energy experts from Chiyoda Corporation online. The feedback helped us verify whether or not several key data inputs, such as the cost and performance parameters of fuel cells, hydrogen liquefaction plants, hydrogenation plants, LOHC trucks, and HRSs were in reasonable range. We conducted desktop studies on a few cases of renewable energy-to-hydrogen projects (Table 14).

[3] Source: CBEA.com news titled "First in the world! 6,547 us fuel cell vehicles sold in the U.S. How about China?" (in Chinese) http://www.cbea.com/yldc/201905/876628.html (accessed 30 Dec 2019)
[4] Source: nbd.com.cn news report titled "Spring in the hydrogen industry? Hydrogen station construction subsidies may be substantially increased" (in Chinese) http://www.nbd.com.cn/articles/2019-03-27/1314957.html (accessed 30 Dec 2019)

Table 14: Hydrogen Energy Demonstration Projects in Japan

Project Name	Project Period	Leading Company or Organisation	Technologies Demonstrated	Hydrogen Energy Supply Capacity
Regional Cooperation and Low-Carbon Hydrogen Technology Demonstration Project	2017–2018	A partnership of the Kanagawa prefectural government and others	Wind energy-to-hydrogen supply system	2 MW of wind power to produce hydrogen at 10 Nm^3/hour, fuelling 12 fuel cell forklifts
Low-Carbon Hydrogen Supply Chain Demonstration Project	2018–present	Toshiba Energy Systems & Solutions, Iwatani	Hydropower to produce hydrogen	200 kW small hydropower generation to produce hydrogen at 35 Nm^3/hour
SPERA Hydrogen	2020–present	AHEAD	Hydrogen supply chain using MCH	210 tons
Hydrogen Energy Supply Chain Pilot Project	2020–2021	HySTRA	Liquefied hydrogen supply chain	3 tonnes (expected to expand after the initial demonstration, as the shipping vessel from KHI has a capacity of 87 tonnes of liquefied hydrogen)
Fukushima Hydrogen Energy Research Field (FH2R)	2020–present	New Energy and Industrial Technology Development Organization		20 MWe of solar PV generation to produce hydrogen at 900 tonnes per year

kW = kilowatt, MW = megawatt, MWe = megawatt-electric, Nm^3 = normal cubic metre.
Source: Authors, based on published reports.

The **Regional Cooperation and Low-Carbon Hydrogen Technology Demonstration Project**, commissioned by the Ministry of the Environment in FY2015, was a partnership of the Kanagawa prefectural government, Yokohama and Kawasaki city governments, Iwatani, Toshiba, Toyota Motor, Toyota Industries, Toyota Turbine and Systems, and Japan Environment Systems. The project announced that a low-carbon hydrogen supply chain that would utilise hydrogen produced from renewable energy in facilities along Tokyo Bay (Yokohama and Kawasaki) to power forklifts had been completed and commenced operation in July 2017.

The project involved a 2 MW wind power generation facility to support electrolysis and deliver hydrogen at 10 Nm^3/hour. The hydrogen was subsequently compressed and transported by a hydrogen refuelling truck to supply 12 fuel cell forklifts.

The project examined future courses of action required to reduce hydrogen costs, verified savings from economies of scale, identified the steps needed towards deregulation, and developed a promotional and deployment model to accelerate technological innovation and advance full-scale supply chains.

The demonstration operation in 2017–2018 showed that fuel cell forklifts had shorter recharging times than electric forklifts, were used flexibly without issues, and were generally well reviewed. However, users requested more frequent hydrogen deliveries to improve fuel cell forklift uptime.

In May 2018, Toshiba Energy Systems & Solutions (Toshiba ESS) announced that they had started a demonstration project in partnership with Iwatani in Kushiro City, Hokkaido Prefecture at a hydrogen production facility using hydrogen produced from a small hydropower plant to establish a hydrogen utilisation model suitable for Hokkaido. The project is proceeding under the Ministry of the Environment's **Low-Carbon Hydrogen Supply Chain Demonstration Project**.[5]

The project uses a 200 kW small hydropower generator and produces hydrogen at 35 Nm^3/hour through electrolysis. The hydrogen is transported by compressed-hydrogen trucks to support several facilities that consume electricity and heat, including a dairy farm, a swimming pool, a welfare and health centre, as well as several FCEVs. Although the specifics of the system's performance are not known, evidence from ENE-FARM applications in Japan implies that the system is highly energy-efficient because it combines electricity and heat. The project's purpose is to verify that the hydrogen energy supply chain is operational.

For long-distance transport of hydrogen, Japan is demonstrating two technical pathways. Chiyoda is leading an alliance to demonstrate large-scale liquid methylcyclohexane (MCH) transport technology, a type of LOHC. The technology produces liquid MCH from toluene and hydrogen, which are maintained in a liquid state at ambient temperatures and pressures, and thus are suitable for transport as a typical liquid chemical product. According to Chiyoda, MCH is as easy to handle as petroleum or natural gas; the technology is branded as **SPERA Hydrogen** by the company.[6]

Chiyoda and its partners, including Mitsubishi, Mitsui, and NYK Line, established the Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD) and started the world's first global hydrogen supply chain demonstration project in 2020, when the Tokyo Olympic Games and Paralympic Games were to have taken place. The project produces hydrogen by steam reforming processed gas derived from the natural gas liquefaction plant of Brunei LNG. The hydrogen is converted into MCH and transported by sea to Japan. The project targets supplying 210 tonnes (maximum) of gaseous hydrogen in 2020, equivalent to fuel demand of 40,000 FCEVs.

Kawasaki Heavy Industry and its partners (J-Power, Shell Japan, Iwatani, Marubeni, JXTG Nippon Oil & Energy, and 'K' Line) from the Hydrogen Energy Supply-chain Technology Research Association (HySTRA) represent the other technical pathway – liquefied-hydrogen transport. The alliance is embarking on a pilot project to demonstrate brown coal gasification and hydrogen refining at Latrobe Valley in Australia, hydrogen liquefaction and storage of liquefied hydrogen at Hastings in Australia, and marine transport of liquefied hydrogen from Australia to Japan in 2020–2021.[7] The project will treat 160 tonnes of inexpensive lignite to produce 3 tonnes of hydrogen. The decision to proceed to a

[5] https://www.toshiba-energy.com/en/info/info2018_0524.htm (accessed on 12 May 2020)
[6] https://www.chiyodacorp.com/en/service/spera-hydrogen/innovations/ (accessed on 12 May 2020)
[7] http://www.hystra.or.jp/en/project/ (accessed on 12 May 2020)

commercial phase will be made in the 2020s, with operations targeted in the 2030s, depending on the successful completion of the pilot phase, regulatory approvals, social license to operate, and hydrogen demand.[8]

The latest development and upscaling of demonstrating how to produce hydrogen energy from renewables is in Fukushima Prefecture. The New Energy and Industrial Technology Development Organization (NEDO) leads the **Fukushima Hydrogen Energy Research Field (FH2R)** with Toshiba ESS, Tohoku Electric Power, and Iwatani. The project will be completed in 2020 at Namie town of Fukushima. FH2R can produce as much as 1,200 Nm^3 of hydrogen per hour (rated power operation) or 900 tonnes per year using renewable energy, mainly from some 20 MW of solar PV capacity. Electrolyser capacity stands at a rated power of 6 MW, with maximum power up to 10 MW. Considering solar energy's intermittency, FH2R is integrated with the local power grid. Hydrogen from the project will be used not only for FCEVs but also for stationary power applications. The project is able to power up to 560 fuel cell passenger cars.

The most important challenge is to use the hydrogen energy management system to optimally combine production and storage of hydrogen and the power grid supply–demand balance without using battery storage. Testing will begin to identify the optimal operation control technology that combines power grid demand response with hydrogen supply and demand response, using units of equipment that have their own operating cycles.[9]

The system is developed to undertake economic evaluation of a hydrogen supply chain based on renewable energy. Under current design and market conditions, the system expects economic return from balancing services for the power grid, hydrogen sales, and electricity sales.

The scale of demonstration of hydrogen and fuel cell technologies and hydrogen supply chains has been increasing in Japan. This implies that technologies, supply chains, and infrastructure are not only maturing but also about to become commercially competitive.

[8] https://hydrogenenergysupplychain.com/about-hesc/ (accessed on 12 May 2020)
[9] https://www.nedo.go.jp/english/news/AA5en_100422.html and https://www.nedo.go.jp/content/100899755.pdf (accessed on 12 May 2020)

Chapter 5

Conclusions and Policy Implications

This study investigated the energy consumption and economic costs of hydrogen as energy storage for renewables in ASEAN and East Asian countries. Downstream, two categories of applications of hydrogen energy were analysed – for the power sector and for the road transport sector. In the case of the power sector, the cost of electricity stored as hydrogen and then returned as electricity to the grid is estimated in US dollars per kilowatt-hour and compared with electricity storage using lithium batteries and pumped hydropower. In the case of transport sector, the total cost of owning and driving FCEVs is estimated in US dollars per kilometre and compared with alternative powertrains such as BEVs, PHEVs, and ICEVs.

Our results show that hydrogen transport and delivery are as important cost drivers as hydrogen production. Amongst the various hydrogen supply pathways, liquefied hydrogen pathways are the costliest. Others, including the compressed gaseous pathways and LOHC pathways, are cheaper. The cost of renewable electricity stored as hydrogen energy and subsequently converted back into electricity by fuel cell is two or three times that of the cost of storage in lithium batteries and pumped hydropower. However, by making use of mature gas turbine technology to convert hydrogen back into electricity, pathways such as compressed hydrogen and pipelines are likely to be competitive against lithium battery storage.

We note that the cost of liquefied hydrogen is extremely high because of the small scale of hydrogen production and transport demonstrated. Leading companies such as KHI believe that the cost of liquefied hydrogen will decrease as it did for liquefied natural gas, especially because liquefaction technology has already developed. KHI foresees that the cost of liquefied hydrogen will soon rapidly decrease.

Such is in line with the economies of scale in the hydrogen energy supply chain observed in our modelling. The described effects are also most evident in the case of liquefied hydrogen pathways. Therefore, as we move from 1,000 MW of RESs to a 4,000 MW source, the cost of electricity stored and transported as liquefied hydrogen will decrease by 50%–70%, depending on the country and the technologies – fuel cell or gas turbine – used to convert hydrogen back into electricity.

In the case of road transport applications, the estimated cost of hydrogen produced from renewables and dispensed to FCEVs through various pathways is typically US$6–US$7/kg, except for the liquefied hydrogen pathway, which is about US$20/kg. Such levels of fuel cost, combined with the high CAPEX of FCEVs, make FCEVs in all three fleets uncompetitive in most of the countries studied. The TCO of FCEVs is typically about two or three times that of BEVs, PHEVs, or ICEVs, except for passenger FCEVs in China. FCEVs enjoy generous government subsidies in China.

We take note that this study, however, did not consider the value of balancing services provided by hydrogen as storage or the value of reduced carbon emissions from FCEVs fuelled by hydrogen sourced from renewables.

We propose that policymakers focus on the following to make hydrogen energy, especially that produced using renewable energy, more competitive: (i) enable economies of scale in hydrogen supply chains, especially those based on renewable energy; (ii) help bring down the high CAPEX of hydrogen supply chains and FCEVs; and (iii) promote new energy market mechanisms to duly value and price the additional benefits of hydrogen energy sourced from renewables, such as balancing the grid against intermittency of renewables and carbon emission reduction.

The cost competitiveness of hydrogen energy and its downstream applications in power and road transport are similar to those of solar PV, wind power, and BEVs 10–20 years ago. Therefore, we have good reason to believe that supportive policies can help hydrogen energy and its related applications accelerate learning effects, economies of scale, and maturing of infrastructure and supply chains, thus substantially cutting the costs of producing and using hydrogen energy.

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