Chapter 3

Quantitative Methodologies and Results

September 2020

This chapter should be cited as

Li, Y. and Taghizadeh-Hesary, F. (2020), 'Quantitative Methodologies and Results', in *Energy Storage for Renewable Energy Integration in ASEAN and East Asian Countries: Prospects of Hydrogen as an Energy Carrier vs. Other Alternatives.* ERIA Research Project Report FY2020 no.9, Jakarta: ERIA, pp.7-20.

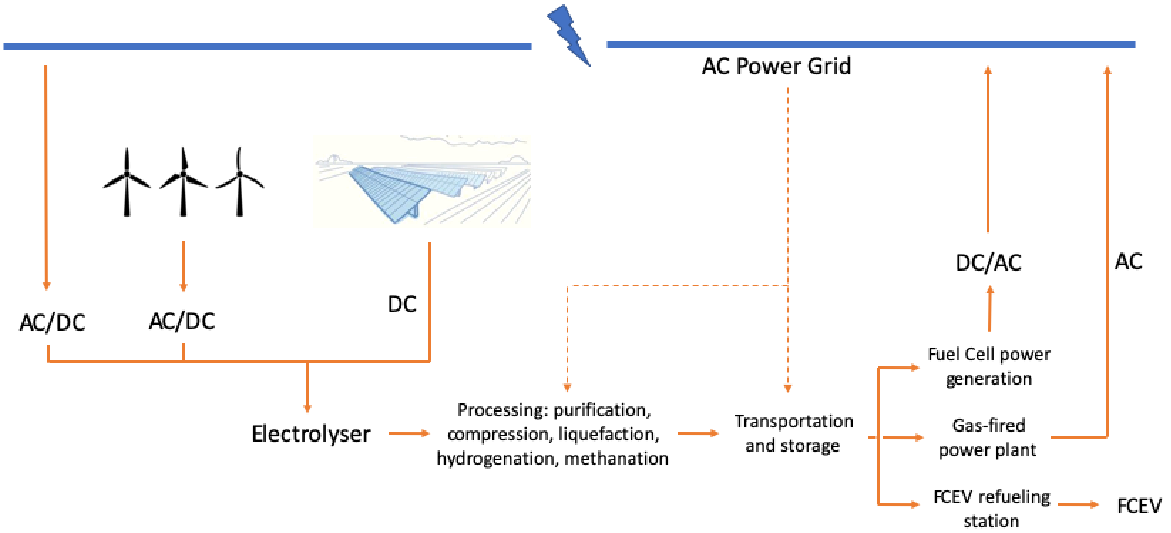
Chapter 3

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

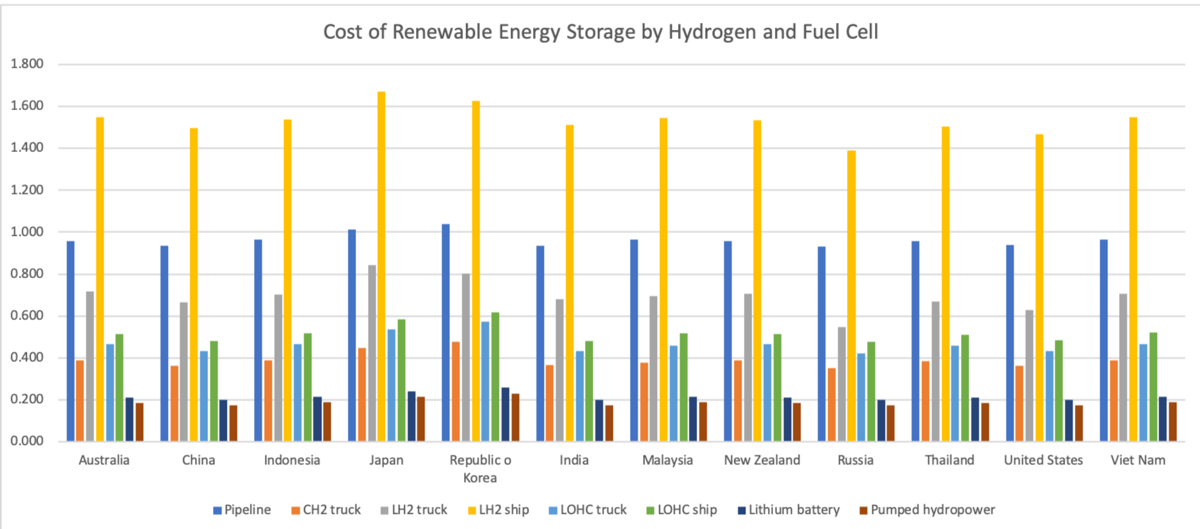
Country	Source of RE	RE Capacity (kW)	Electrolyser	System Utilisation Rate / Capacity Factor	Transport	Transport Scenario	Storage	Refilling Station	Duration of Storage (days)	Storage Means
China	SPV	4000000	PEM	80%	LOHC truck	Domestic medium distance	Yes	Small	7	Gaseous geological storage (Pressurized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



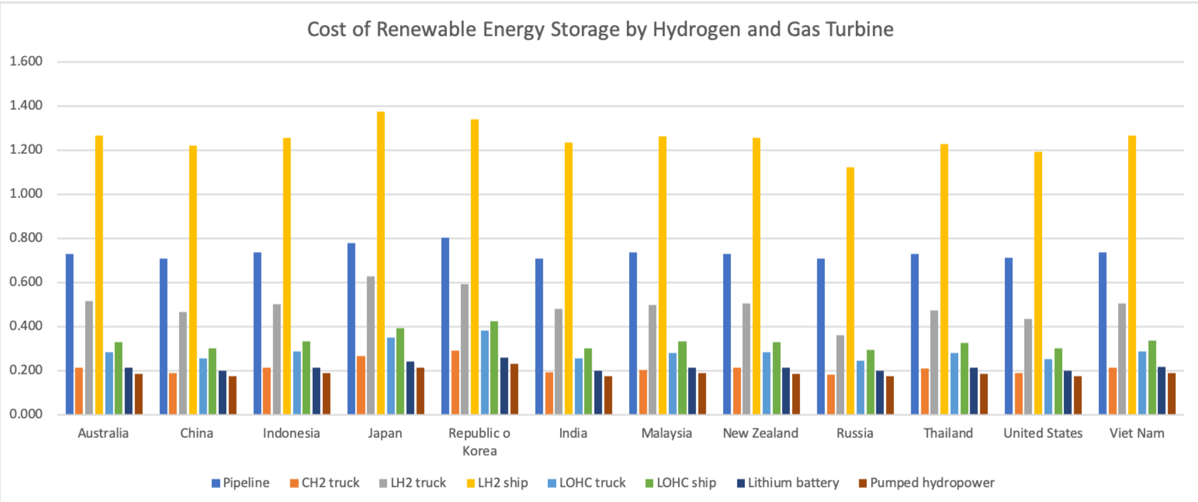
CH_2 = compressed hydrogen, kWh = kilowatt-hour, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

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.

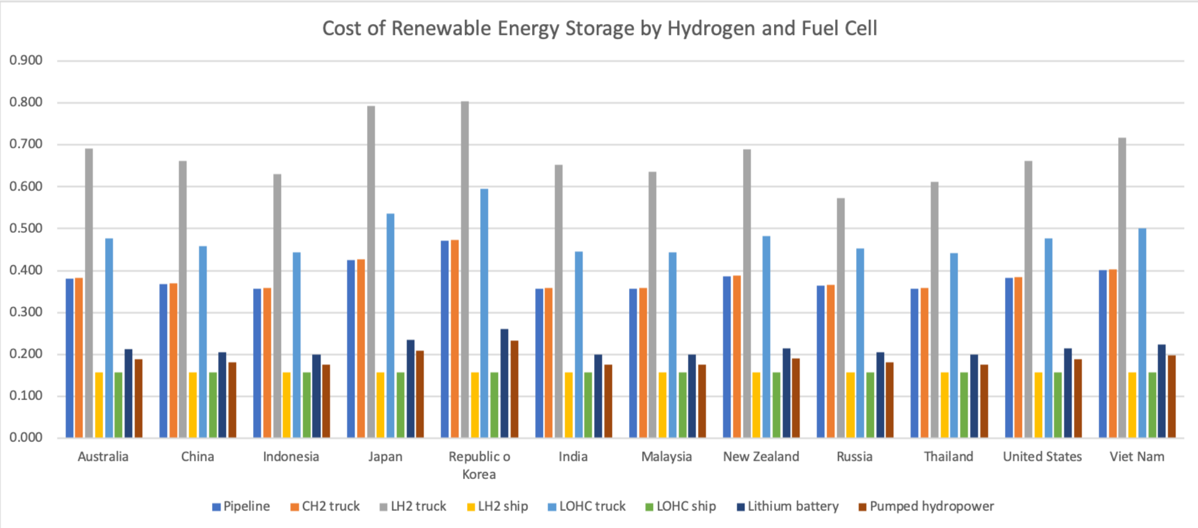
Figure 7: Cost of Storing Solar Energy as Hydrogen and Generating Electricity Using Gas Turbine (US$/kWh)



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.

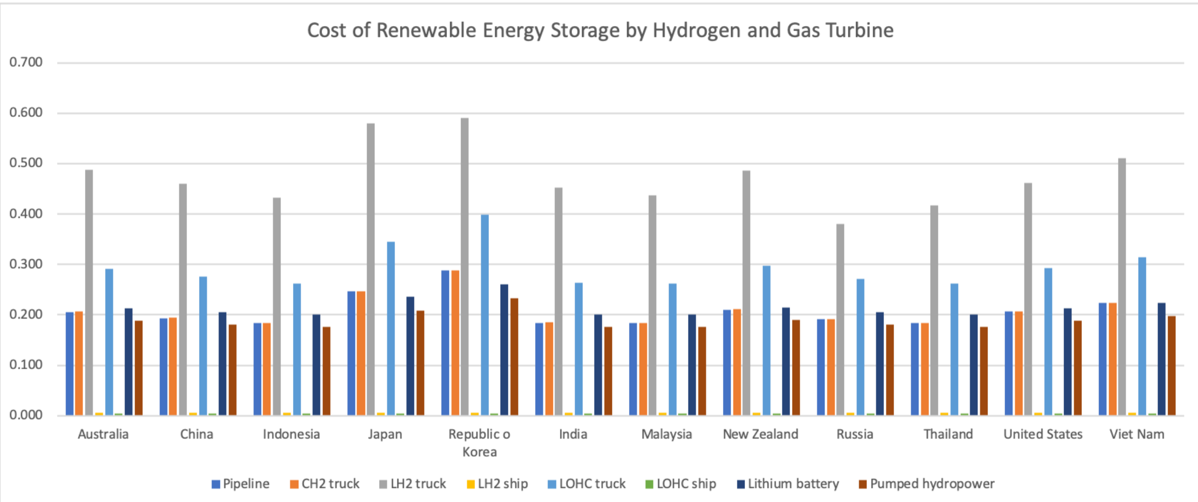
Figure 8. Cost of Storing Wind Energy as Hydrogen and Generating Electricity Using Fuel Cell (US$/kWh)



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)

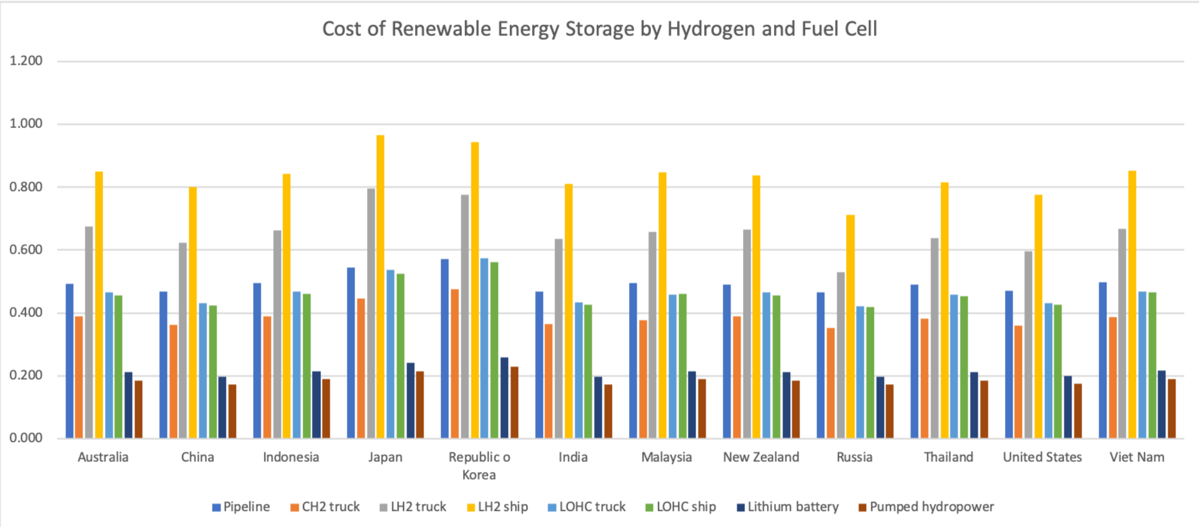


CH_2 = compressed hydrogen, kWh = kilowatt-hour, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

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.

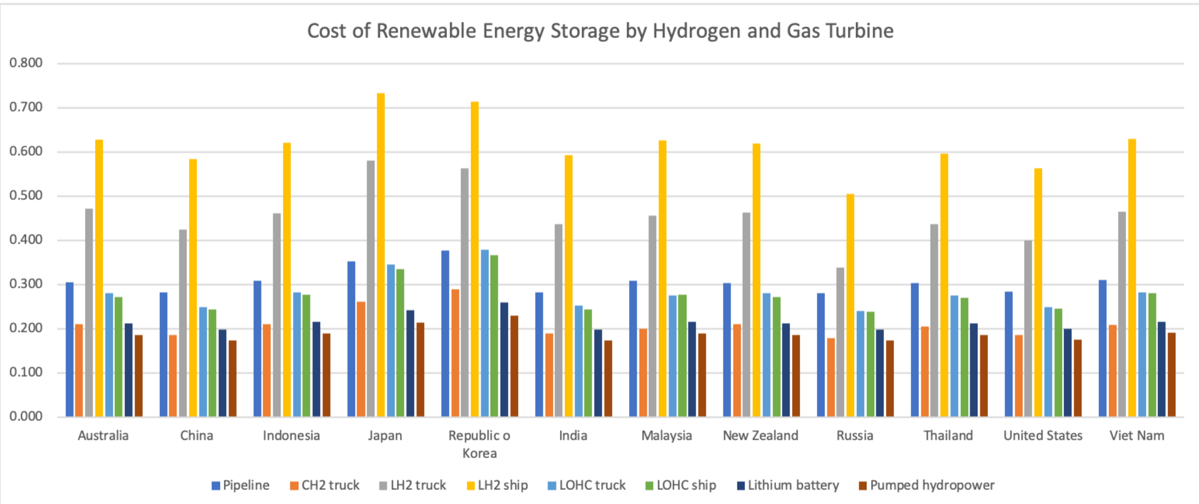
Further experiments with our model show that the hydrogen supply chain has significant economies of scale, which would lower the delivered cost per kilowatt-hour of stored energy if, say, we increased RESs to 4,000 MW. Figure 10 and Figure 11 present such economy of scale for solar as the source of energy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



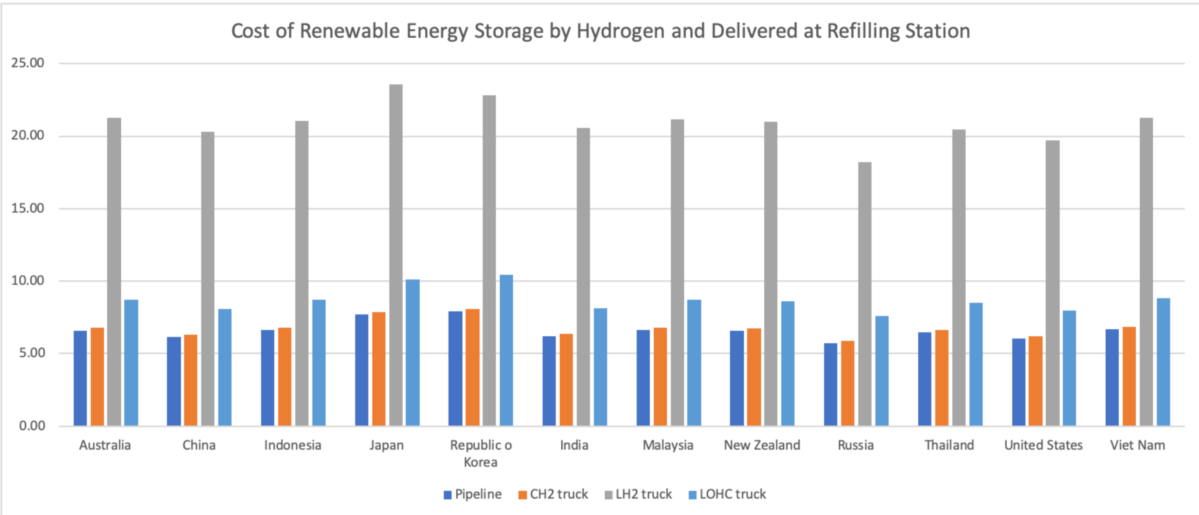
CH_2 = compressed hydrogen, kWh = kilowatt-hour, LH_2 = liquid hydrogen, LOHC = liquid organic hydrogen carrier.
Source: Authors.

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.

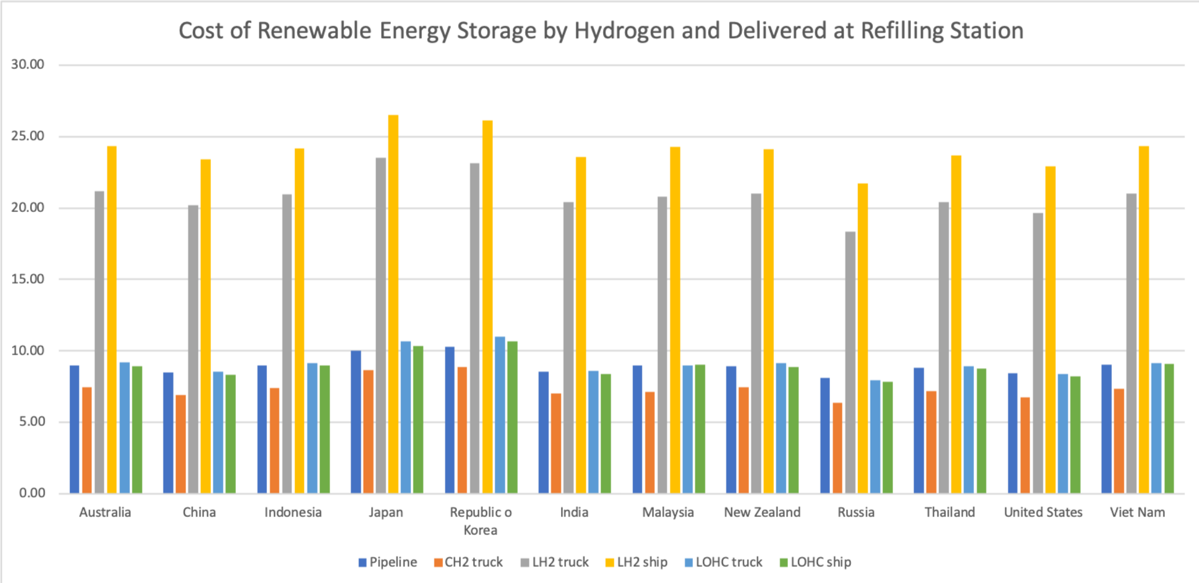
Figure 12. Cost of Storing Solar Energy as Hydrogen and Delivered at Refuelling Station (domestic medium distance) (US$/kg)



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.