Chapter 5

Energy Consumption, Carbon Emissions, and Hydrogen Supply Chain and Fuel Cell Electric Vehicle Costs in ASEAN Countries

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Chapter 5

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1. Motivation and Methodology

Commercialisation of hydrogen as an alternative to fossil fuels is still economically challenging. According to the US Department of Energy, the cost of hydrogen production from centralised or distributed electrolysis in 2015 was US$3–$3.9/kg, short of the targeted cost of $2/kg.[1]

Questions remain as to whether deployment of hydrogen-based powertrains, namely fuel cell electric vehicles (FCEVs), for ASEAN countries' passenger car, bus, and truck fleets can be reasonably justified, given the technological outlook. If not, it is worth understanding how big the economic gaps of hydrogen supply chains are, and from what parts of the supply chain they stem. This will also inform which FCEV application niches could be prioritised, as they are most likely to become competitive in the near future.

Specifically, this study aims to model the well-to-wheel (WTW) energy, carbon emissions, and cost profile of a hydrogen supply chain. In addition, at the user end of hydrogen applications, as a fuel for the land transport sector, the energy consumption, carbon emissions, and economics will be analysed as against alternatives, including conventional fossil fuels for internal combustion engine vehicles (ICEVs), as well as battery-based electric vehicles (BEVs). A total cost of ownership (TCO) concept will be applied in this regard.

WTW and TCO models that cover both the upstream and downstream of the hydrogen economy will be developed using Excel Macro, capable of simulating various scenarios, assuming different technologies, industrial processes, environmental parameters, resource endowments, market setups, and energy and industrial policies. Reasonable assumptions about these key factors will be able to precisely indicate the economic and environmental feasibility of hydrogen supply chains, as well as a hydrogen economy.

2. A Review of Past WTW and TCO Studies on Hydrogen Supply Chains

Ally and Pryor (2016) conducted a TCO analysis, applying a lifecycle assessment framework on the application of fuel cell buses (FCBs) compared to diesel, compressed natural gas, and hybrid buses, operated between 2012 and 2014 in Australia. The study found that at the current level of capital and operation costs and with current performances of hydrogen and fuel cell technologies, the TCO of an

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[1] source: https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-production-electrolysis

FCB is 2.6 times that of a conventional diesel bus. Even if the US Department of Energy's long-term targets (Spendelow and Papageorgopoulos, 2012) about FCB capital and operating expenditure are achieved, a gap of A$400,000+ between the two technologies' TCO would remain. The study assumed that the cost of hydrogen is between A$20.90/kg and A$22.40/kg, if the electricity cost is A$0.26/kWh and small-scale on-site production is applied. At such TCO levels, FCBs cannot compete with either hybrid or compressed natural gas buses (compressed natural gas bus TCOs are 36% higher than those for a diesel bus, due to high cost of natural gas). However, if diesel prices increase to A$4.5/L from the current level of A$1.388/L, FCBs' TCO can break even with that of diesel buses, at A$19/kg. Capital expenditure, followed by the cost of hydrogen, is the largest driver of FCBs' TCO. It is noted that this study assumed no FCB end-of-life value after the assumed 15 years' usage.

An earlier WTW study by Cockroft and Owen (2007) considered the external value of environmental impacts by various powertrain technologies for urban buses, taking as a case study the bus fleet in Perth, Australia. This study assumes an initial capital cost of the hydrogen FC bus as about 29% higher than conventional diesel buses, which cost US$418,400 each, a very aggressive assumption following the US Department of Energy's long-term targets of US$30/kW for fuel cell stacks and an average of US$15/kW of complementary infrastructure cost. It also assumed an idealistic cost of hydrogen fuel at US$5/kg. With such favourable assumptions for hydrogen FC buses, there is still a gap of US$265,800 between the net present value of the total private cost of operation for the 15-years lifetime of a diesel bus and that of a hydrogen FCB. This gap can be reduced to US$169,000, when the social costs of urban air pollution, as well as climate change due to greenhouse gas (GHG) emissions, are considered. In more aggressive scenarios, in which either fossil fuel costs increase faster in future or the environmental costs surge to higher values, the gap can be bridged or even reversed.

A lifecycle cost analysis was conducted by Cockroft and Owen (2017), reporting the levelled cost of hydrogen, on a well-to-tank basis, from a real and small distributed water electrolysis project in Belgium, which produces hydrogen from wind power, as well as grid electricity. The reported data were collected up to 2015. The reported cost of hydrogen dispensed was EUR13.9/kg. The cost is mostly driven by feedstock, followed by capital and operational costs. This is compared to a range of costs varying from EUR2.8/kg to EUR27.5/kg documented in previous literature.

Nguyen et al. (2013) conducted a WTW analysis on the carbon emissions of mid-size light duty vehicles applying various powertrains in a 2035 scenario, covering ICEVs, hybrid vehicles, plug-in hybrid vehicles, range-extension electric vehicles, BEVs, and fuel cell electric vehicles (FCEVs). In the case of the first three, various fuel sources, including renewables with various blending levels are applied. FCEVs powered by hydrogen sourced from wind as well as biomass production pathways have the potential to deliver the lowest carbon emissions. This is followed by hydrogen produced from natural gas and coal with carbon capture. Plug-in hybrid vehicles and range-extension electric vehicles are amongst the second league in delivering lower carbon emissions, if biofuel and electricity from renewable sources are applied.

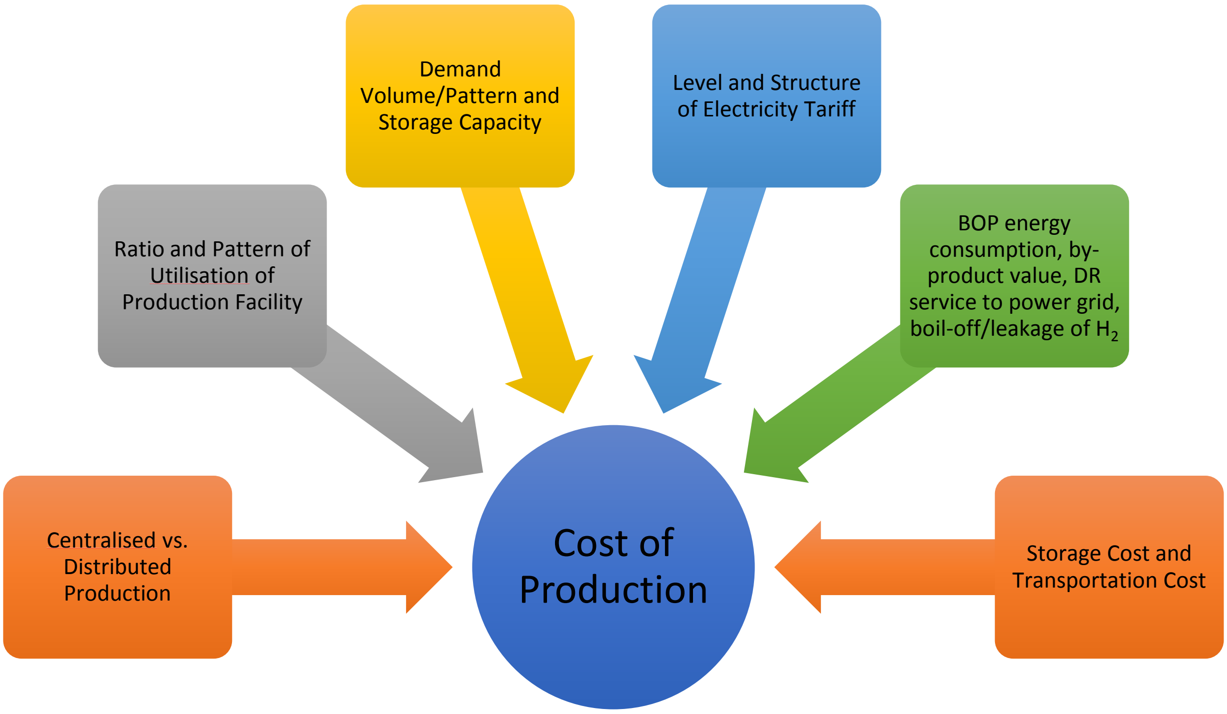
3. Model Description, Data, and Scenarios

3.1. General Description of the Model

This study builds a WTW model to capture the energy production and consumption process, as well as the costs and emissions involved. Based on the WTW concept, a TCO is further developed to access the cost of owning, as well as driving, a vehicle through its lifetime. The studied vehicle fleets include mid-size passenger cars, buses, and heavy-duty trucks.

Key factors determining the costs of hydrogen production pathways are modelled in Figure 5.1:

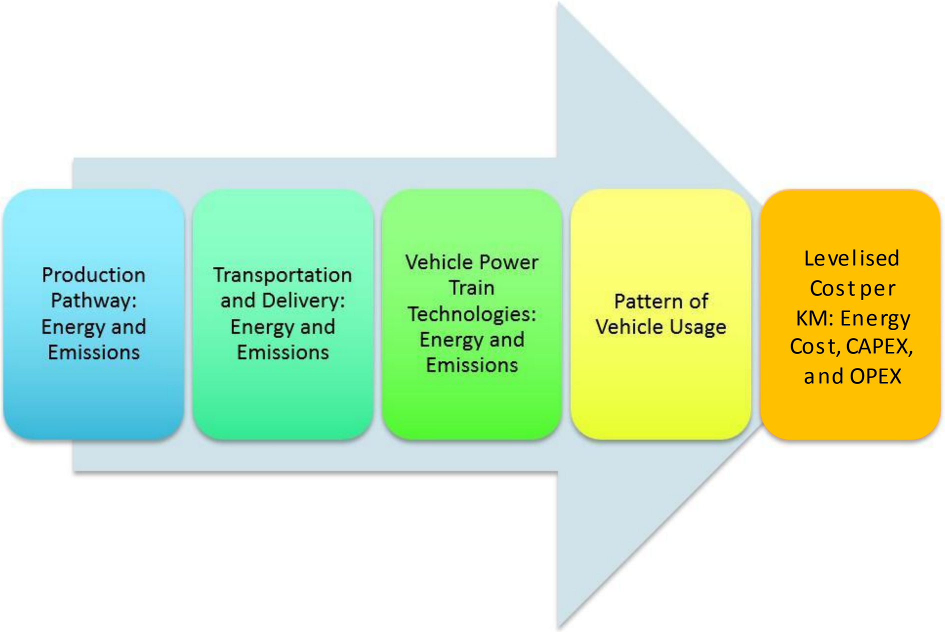
Figure 5.1 Key Factors Considered in Modelling the Hydrogen Production Pathways



BOP = balance of plants, DR = demand response.
Source: Authors.

Figure 5.2 shows the results of modelling the TCO of vehicles:

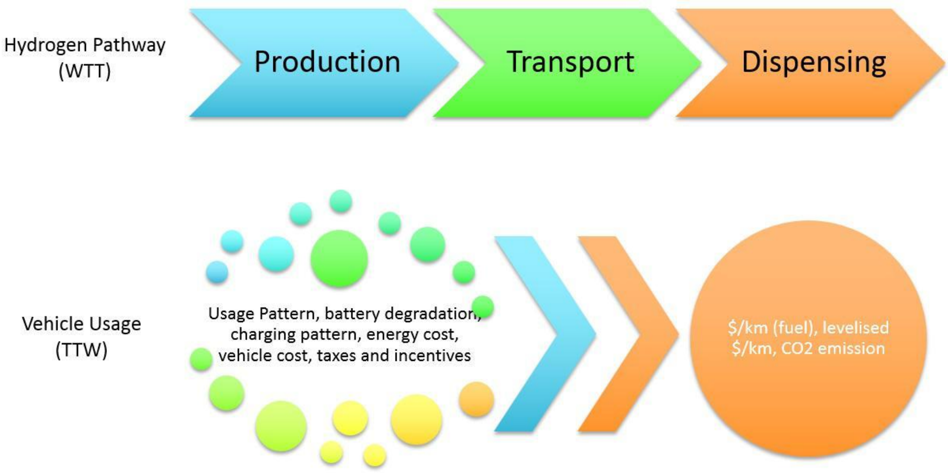
Figure 5.2 Key Factors Considered in Modelling the TCO of Vehicles



TCO = total cost of ownership, CAPEX = capital expenditure, OPEX = operating expenditure.
Source: Authors.

Figure 5.3 shows the relationship of between the WTW model and the TCO model. Basically, TCO is integrated into the TTW part of the WTW.

Figure 5.3 Well-to-Tank, Tank-to-Wheel, and Total Cost of Ownership



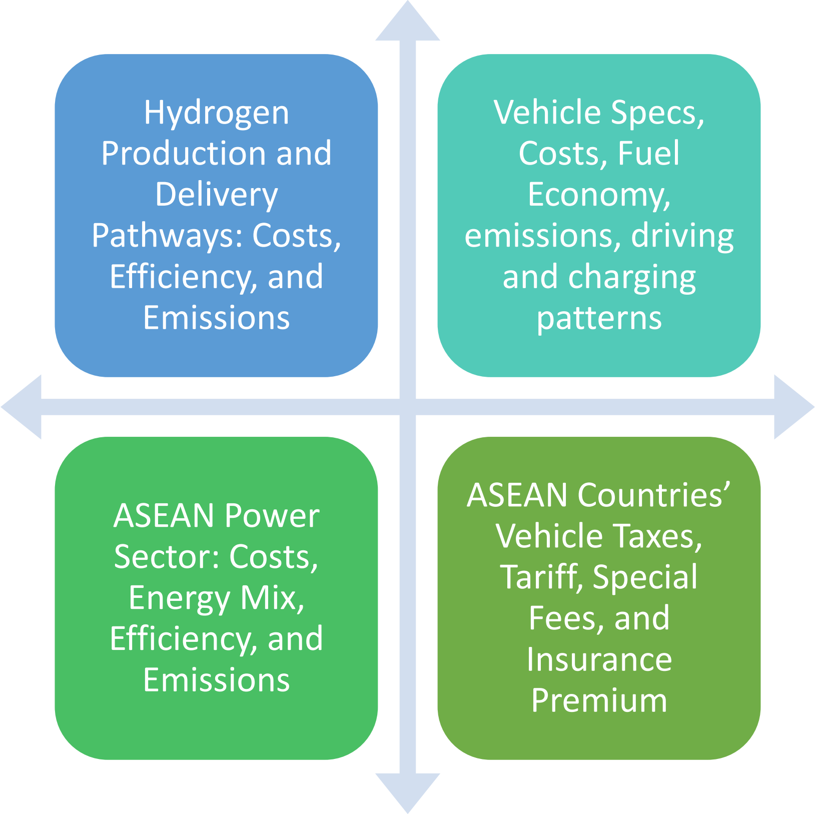
TTW = Tank-to-Wheel, WTT = Well-to-Tank.
Source: Authors.

3.2. Data Description

There are four major blocks of data inputs used in the models, as shown in Figure 5.4. The estimated production efficiency and costs of hydrogen pathways, as well as those for the transportation and dispensing of hydrogen, are collected from international sources, including US and Japan data. To apply the ASEAN countries' specific cases, the power generation sector is typically surveyed, covering the cost of electricity production, the energy mix, and GHG emissions of the power sector.

Data about vehicle specifications (such as engine size, battery size, and fuel cell stack size), costs and fuel economy are collected from international open market sources. To study the ASEAN countries' specific position in applying these vehicle technologies, data about the various vehicle taxes, tariffs, special fees, and insurance premiums are surveyed.

Figure 5.4 Four Major Blocks of Data Inputs



Source: Authors.

3.3. Scenarios

There are three dimensions along the hydrogen supply chain in which infrastructure changes will significantly influence both the costs and emissions level of the fuel. The first dimension is the choice of the mix of pathways, i.e., what percentage of the hydrogen supply is from which production pathway. The second dimension is the choice of the production mode, i.e., centralised or distributed (forecourt). The third dimension is the choice of the transportation and delivery network, i.e., the use of pipelines, compressed gas tube trailers, liquid tube trailers, with or without a storage function and gaseous or liquid hydrogen dispensing at a refuelling station. Accordingly, this study first creates a benchmark scenario, with fixed assumptions applying to all covered countries. This is followed by scenarios that vary from the benchmark, as a sensitivity test.

Since the technologies for both hydrogen supply chains and fuel cells are expected to go through significant breakthroughs in performance, as well as decreases in costs, future scenarios are also created to see how these developments will affect the competitiveness of hydrogen-based solutions for the road transport sector, as compared to other alternative powertrain solutions.

3.4. Benchmark Scenario

In the benchmark scenario, ASEAN countries are expected to apply a portfolio of hydrogen production as shown in Table 5.1, for both centralised and distributed pathways.

Table 5.1: Share of Pathways in the Benchmark Scenario (in %)

Country	Natural Gas Reforming	Lignite Gasification	Biomass Gasification	Solar PV	Wind
Brunei Darussalam	40	30	10	10	10
Cambodia	40	30	10	10	10
Indonesia	40	30	10	10	10
Lao PDR	40	30	10	10	10
Malaysia	40	30	10	10	10
Myanmar	40	30	10	10	10
Philippines	40	30	10	10	10
Thailand	40	30	10	10	10
Singapore	40	30	10	10	10
Viet Nam	40	30	10	10	10

Lao PDR = Lao People’s Democratic Republic, PV = photovoltaics.
Source: Authors.

Regarding the choice of transportation and dispensing means, the benchmark results will have two variations. The first set of assumptions is to apply forecourt production with compressed gas dispensing, without storage. The second set is to apply centralised production with gaseous tube trailer transportation and compressed gas dispensing, with storage.

3.5. Sensitivity Analysis

As shown in Table 5.2, the comparative scenario assesses whether a higher share of renewables-based pathways could shift the relative competitiveness of FCEV powertrains against other alternative powertrains.

Table 5.2 Share of Pathways in the Alternative Scenario (in %)

Country	**Natural Gas Reforming**	**Lignite Gasification**	**Biomass Gasification**	**Solar PV**	**Wind**
Brunei Darussalam	25	15	20	20	20
Cambodia	25	15	20	20	20
Indonesia	25	15	20	20	20
Lao PDR	25	15	20	20	20
Malaysia	25	15	20	20	20
Myanmar	25	15	20	20	20
Philippines	25	15	20	20	20
Thailand	25	15	20	20	20
Singapore	25	15	20	20	20
Viet Nam	25	15	20	20	20

Lao PDR = Lao People's Democratic Republic, PV = photovoltaics.
Source: Authors.

To ensure comparability, the choice of transportation and dispensing means applies the same assumptions as in the benchmark scenario.

3.6. Future Scenarios

Future scenarios will separately check the capital cost outcome of FCEVs decreasing by 50% to 70%, that of the production cost of renewables-based pathways decreasing by 50%, and that of the transportation and dispensing costs also decreasing by 50%. These effects will be aggregated in this scenario to show the impacts of progresses in technology, as well as economies of scale and learning effects, by circa 2030. The expected changes in the prices of fossil fuel and grid electricity are also considered.

Regarding the choice of transportation and dispensing means, the future scenarios will also have two variations. The first set of assumptions is to apply forecourt production with compressed gas dispensing, without storage. The second set is to apply centralised production with liquid tube trailer transportation and liquid gas dispensing, with storage.

4. Simulation Results: Energy Consumption, Carbon Emissions, and Costs of FCEVs and Other Alternatives

4.1. Benchmark and Sensitivity Scenarios

This section summarises the results of the benchmark scenario, which compares the energy use, carbon emissions, and economics of the four different powertrains applied in each of the passenger car, bus, and truck fleets. In the scenario, forecourt and centralised hydrogen production are compared. This assumes that fossil fuels such as coal and natural gas dominate the production of hydrogen. All results of this scenario are then compared to a sensitivity scenario, in which renewables will dominate the production of hydrogen. Lastly, all results can be compared to those from the future scenario, in which the production cost of hydrogen, capital cost of FCEVs, and the costs of transportation and delivery of hydrogen are assumed to be 50% lower than the current levels by approximately 2030.

Table 5.3 presents the primary energy consumption per km, carbon emissions per km, TCO per km, as well as fuel cost per km of FCEVs consuming hydrogen produced from forecourt production, in comparison with those of the vehicles with alternative powertrains. The numbers presented are the outcome of an unweighted average of all ASEAN countries. Detailed results for each country are available upon request.

Table 5.3 Benchmark Scenario with Forecourt Production of Hydrogen: ASEAN Average Levels

		WTW Primary Energy (kWh/km)	**WTW CO_2 Emissions (kg/km)**	**TCO ($/km)**	**Fuel Cost ($/km)**
Passenger Cars	FCEV	0.528	0.109	0.684	0.083
	BEV	0.223	0.093	0.529	0.024
	PHEV	0.415	0.146	0.454	0.050
	ICEV	0.392	0.132	0.326	0.048
Buses	FCEV	1.401	0.290	2.658	0.220
	BEV	1.587	0.662	1.110	0.170
	PHEV	2.537	0.886	1.515	0.305
	ICEV	4.700	1.586	1.289	0.576
Trucks	FCEV	7.076	1.463	2.037	1.109
	BEV	1.521	0.635	0.648	0.163
	PHEV	2.777	0.937	0.688	0.340
	ICEV	3.610	1.219	0.728	0.442

ASEAN = Association of Southeast Asian Nations, BEV = battery electric vehicle, FCEV = fuel cell electric vehicle, ICEV = internal combustion engine vehicle, PHEV = plug-in hybrid electric vehicle, TCO = total cost of ownership, WTW = well-to-wheel.
Source: Authors.

According to our model's estimation, centralised production, which assumes a 100 km supply chain from production to dispensing, with storage, will incur a higher fuel cost and thus TCO per km. The results of a benchmark scenario with centralised production of hydrogen is presented below in Table 5.4. Since this is only relevant to FCEVs, the results of vehicles with other powertrains remain the same as in Table 5.3. In short, centralised production of hydrogen leads to less primary energy consumption, as well as fewer carbon emissions, from FCEVs due to their higher efficiency compared to forecourt production. However, the cost of hydrogen would be higher, due to the need of transportation, which is costly.

Table 5.4 Benchmark Scenario with Centralised Production of Hydrogen: ASEAN Average Levels

	WTW Primary Energy (kWh/km)	WTW CO_2 Emissions (kg/km)	TCO ($/km)	Fuel Cost ($/km)
FCEV Passenger Car	0.529	0.111	0.690	0.089
FCEV Bus	1.395	0.289	2.673	0.235
FCEV Truck	7.046	1.458	2.115	1.187

ASEAN = Association of Southeast Asian Nations, FCEV = fuel cell electric vehicle, TCO = total cost of ownership, WTW = well-to-wheel.
Source: Authors.

In the sensitivity scenario, hydrogen is predominantly produced from renewables. As Table 5.5 and Table 5.6 show for forecourt production and centralised production of hydrogen, respectively, such will lead to even lower carbon emissions from FCEVs, from a WTW perspective, compared to other powertrains. However, under current technologies of renewable energy, fuel costs for FCEVs will be higher. Again, since the centralised production of hydrogen is only relevant to FCEVs, the results of vehicles with other powertrains remain the same as in Table 5.3.

Table 5.5 Sensitivity Scenario with Forecourt Production of Hydrogen: ASEAN Average Levels

	WTW Primary Energy (kWh/km)	WTW CO_2 Emissions (kg/km)	TCO ($/km)	Fuel Cost ($/km)
FCEV Passenger Car	0.574	0.067	0.702	0.100
FCEV Bus	1.524	0.177	2.703	0.265
FCEV Truck	7.696	0.893	2.264	1.336

ASEAN = Association of Southeast Asian Nations, FCEV = fuel cell electric vehicle, TCO = total cost of ownership, WTW = well-to-wheel.
Source: Authors.

Table 5.6 Sensitivity Scenario with Centralised Production of Hydrogen: ASEAN Average Levels

	WTW Primary Energy (kWh/km)	WTW CO_2 Emissions (kg/km)	TCO ($/km)	Fuel Cost ($/km)
FCEV Passenger Car	0.575	0.068	0.707	0.106
FCEV Bus	1.517	0.176	2.718	0.280
FCEV Truck	7.663	0.891	2.343	1.415

ASEAN = Association of Southeast Asian Nations, FCEV = fuel cell electric vehicle, TCO = total cost of ownership, WTW = well-to-wheel.
Source: Authors.

Based on such results, the following observations are made:

1. The application of FCEVs as passenger cars and buses delivers fewer carbon emissions than vehicles with other powertrains.
2. In the case of FCEV buses, primary energy consumption and fuel cost per km are lower than buses with other powertrains.
3. In all cases, the TCO expressed in dollars per km of FCEVs in all fleets is the highest amongst all types of vehicles. In the case of fuel cell trucks (FCTs), the TCO gap is exceptional. This is mostly due to FCTs still being in the prototype stage, as well as FCT capital costs not being directly available from open sources.
4. If hydrogen is mostly produced from renewable sources, carbon emissions become the lowest amongst all powertrains in the passenger car and bus fleets. In the case of the truck fleet, FCEV carbon emissions are lower than that of the diesel truck. However, such comes at the price of higher fuel cost per km for FCEVs.
5. In the case of FCTs, the relatively low fuel economy, even compared to diesel trucks, is an obvious disadvantage. This may be attributed to fuel economy data of FCTs being rarely disclosed with sufficient details.

4.2. The Future Scenario

Tables 5.7 and 5.8 present the results of the future scenario from our model.

Table 5.7 Future Scenario with Forecourt Production of Hydrogen: ASEAN Average Levels

		WTW Primary Energy (kWh/km)	WTW CO_2 Emissions (kg/km)	TCO ($/km)	Fuel Cost ($/km)
Passenger Cars	FCEV	0.528	0.109	0.376	0.046
	BEV	0.223	0.093	0.531	0.040
	PHEV	0.415	0.146	0.484	0.090
	ICEV	0.392	0.132	0.294	0.090
Buses	FCEV	1.401	0.290	1.426	0.123
	BEV	1.587	0.662	1.184	0.283
	PHEV	2.537	0.886	1.755	0.550
	ICEV	4.700	1.586	1.912	1.208
Trucks	FCEV	7.076	1.463	1.167	0.622
	BEV	1.521	0.635	0.691	0.271
	PHEV	2.777	0.937	0.969	0.621
	ICEV	3.610	1.219	1.114	0.831

ASEAN = Association of Southeast Asian Nations, BEV = battery electric vehicle, FCEV = fuel cell electric vehicle, ICEV = internal combustion engine vehicle, PHEV = plug-in hybrid electric vehicle, TCO = total cost of ownership, WTW = well-to-wheel.
Source: Authors.

Table 5.8 Future Scenario with Centralised Production of Hydrogen: ASEAN Average Levels

	WTW Primary Energy (kWh/km)	WTW CO_2 Emissions (kg/km)	TCO ($/km)	Fuel Cost ($/km)
FCEV Passenger Car	0.529	0.111	0.3789	0.049
FCEV Bus	1.395	0.289	1.433	0.131
FCEV Truck	7.046	1.458	1.064	0.661

ASEAN = Association of Southeast Asian Nations, FCEV = fuel cell electric vehicle, TCO = total cost of ownership, WTW = well-to-wheel.
Source: Authors.

The following observations draw on the future scenario.

1. In the 2030 scenario, with 50% reduction in the capital cost of FCEVs and 50% reduction in the hydrogen fuel costs (including production, transportation, and dispensing), the TCO of FCEVs in terms of dollars per km largely becomes competitive against fossil fuel-powered vehicles, especially in the bus and truck fleets

2. In terms of fuel cost per km, FCEVs also become competitive against fossil fuel-powered vehicles in all three fleets
3. If the capital cost of FCEVs can be cut by 70%, they become the most competitive in terms of both TCO and fuel cost per km in all three fleets

4.3. Country-specific Results

Each ASEAN country has its unique taxes, tariffs, fees and surcharges, as well as incentives and subsidies imposed, on the purchase and use of vehicles. The ASEAN countries also differentiate with their unique power generation mix and thus the costs and emissions of each kWh of electricity. These drive the models' differentiated results. The key observations about each country are summarised in Table 5.9. In each cell, FCEVs' performance or competitiveness is compared to other powertrains in a certain fleet, and ranked, with 1 being the best and 4 being the worst.

Table 5.9 Summary of Key Observations of Each ASEAN Country in the Benchmark Scenario with Forecourt Production

Country	fleet	Energy use / km	CO_2 / km	TCO / km	Fuel cost / km
Brunei Darussalam	Passenger Car	4	1	4	4
	Bus	1	1	4	3
	Truck	4	4	4	4
Cambodia	Passenger Car	4	1	4	4
	Bus	1	1	4	1
	Truck	4	4	4	4
Indonesia	Passenger Car	4	1	4	4
	Bus	1	1	4	3
	Truck	4	4	4	4
Lao PDR	Passenger Car	4	2	4	4
	Bus	1	2	4	2
	Truck	4	4	4	4
Malaysia	Passenger Car	4	1	4	4
	Bus	1	1	4	2
	Truck	4	4	4	4
Myanmar	Passenger Car	4	2	4	4
	Bus	1	1	4	2
	Truck	4	4	4	4
Philippines	Passenger Car	4	2	4	4
	Bus	1	1	4	1

	Truck	4	4	4	4
Singapore	Passenger Car	4	2	4	4
	Bus	1	1	4	2
	Truck	4	4	4	4
Thailand	Passenger Car	4	2	4	4
	Bus	1	1	4	2
	Truck	4	4	4	4
Viet Nam	Passenger Car	4	2	4	4
	Bus	1	1	4	2
	Truck	4	4	4	4

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic, TCO = total cost of ownership.
Source: Authors.

Table 5.10 presents the results from the future scenario (year 2030), with forecourt production of hydrogen as a comparison to the previous table.

Table 5.10 Summary of Key Observations of Each ASEAN Country in the Future Scenario with Forecourt Production

Country	fleet	Energy use / km	CO_2 / km	TCO / km	Fuel cost / km
Brunei Darussalam	Passenger Car	4	1	3	3
	Bus	1	1	3	2
	Truck	4	4	4	3
Cambodia	Passenger Car	4	1	2	1
	Bus	1	1	3	1
	Truck	4	4	4	4
Indonesia	Passenger Car	4	1	3	2
	Bus	1	1	4	2
	Truck	4	4	4	3
Lao PDR	Passenger Car	4	2	2	2
	Bus	1	2	4	1
	Truck	4	4	4	4
Malaysia	Passenger Car	4	1	3	2
	Bus	1	1	4	1
	Truck	4	4	4	3
Myanmar	Passenger Car	4	2	4	2
	Bus	1	1	4	2
	Truck	4	4	4	3
Philippines	Passenger Car	4	2	2	1
	Bus	1	1	2	1
	Truck	4	4	4	4
Singapore	Passenger Car	4	2	3	2
	Bus	1	1	4	1
	Truck	4	4	4	4
Thailand	Passenger Car	4	2	2	2
	Bus	1	1	2	1
	Truck	4	4	4	4
Viet Nam	Passenger Car	4	2	2	2
	Bus	1	1	3	1
	Truck	4	4	4	3

ASEAN = Association of Southeast Asian Nations, Lao PDR = Lao People's Democratic Republic, TCO = total cost of ownership.

Source: Authors.

5. Key Observations

The following observations draw on the above-reported results and findings:

1. The higher TCO of FCEVs is driven by the very high capital expenditure of the vehicles.
2. FCEVs are also estimated to have higher costs for fuel transportation and dispensing.
3. Hydrogen production pathways are not yet competitive, except for those based on natural gas, coal and biomass.
4. These disadvantages are highly likely to be overturned as continuous R&D brings about technological breakthroughs, combined with the effects of the learning curve and economies of scale, when H_2 supply chains, H_2 transmission and distribution infrastructure and manufacturing of FCEVs come into commercial operation.
5. If renewables-based hydrogen supply chains' GHG benefit is considered, the advantages of H_2 will further boost its competitiveness against other alternative powertrains.
6. Although FCEVs are not yet competitive, the results indicate a future in which FCEVs will become competitive under certain circumstances and in certain application scenarios.
7. Indonesia and the Philippines seem to be closer to bridging the commercial feasibility gaps of FCEVs in the future.
8. FCEV buses will be the most promising application of hydrogen-based powertrains to replace conventional ones.
9. This study has quantified the gaps in both TCO and fuel cost per km, and the policy support in the form of various subsidies, tax incentives and RD&D that can help accelerate the arrival of this future scenario.
10. Pricing emissions will also help bridge the gap in the economic competitiveness of hydrogen-based powertrains to compete with conventional as well as other alternative powertrains.

The availability of high-quality data regarding the technical performances of hydrogen production pathways, hydrogen transportation and storage, hydrogen refuelling stations, and the fuel economy of FCEVs, especially regarding trucks, remain the main limitation of this study. The currently reported results reflect the best available data from the public domain.

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