Well-to-wheel comparison of emissions and energy consumption for electric vehicles: Oceanian perspective

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Abstract

Although electric vehicles are widely accepted to be the pathway for minimising traffic emissions, those powered by fossil dominated power sources may be a limited solution to reducing emissions. This study presents a comparative study of the Australian and New Zealand vehicle markets on emissions and energy consumption using well-to-wheel analysis. A vehicle uptake model is developed, based on sales targets set by both countries to study the long-term impacts of electric vehicles through 2050. Empirical results suggest that large-scale uptake of battery electric vehicles is an environmentally viable option for New Zealand, but it makes sense only for a limited driving distance due to the heavy battery. In Australia, from a strictly environmental perspective, hydrogen-powered electric vehicles offer the best long-term solution given its current electricity generation mix. The analysis results deliver important policy insights for decision makers both in the Oceanian region and other countries with similar characteristics.

Keywords:

Greenhouse gas emission; Electric vehicles; Energy consumption; Well-to-wheel; Electricity generation mix; Hydrogen

1. Introduction

According to the International Energy Agency (IEA), transportation accounted for the second-highest source of carbon dioxide (CO_2) emission, making up to 25% of the total 33 gigatons (Gt) of CO_2 emission in 2018, right after the industrial sector (IEA, 2019a). The transportation sector was also responsible for the largest share of global energy consumption (35%) in 2017 (IEA, 2019b). There is a growing need for transformational technologies within the transportation sector to address future energy demand, and to minimise its carbon footprint simultaneously by seeking alternatives to replace the current vehicle fleet, which is dominated by conventional Internal Combustion Engine (ICE).

Over the past decade, with an increasing consensus about climate change issues and environmental degradation, Electric Vehicles (EVs) are increasingly seen as a low or zero emission transport alternative. EVs are vehicles running on an electric motor powered by

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batteries entirely or partially. From an environmental perspective, EVs are considered as the future of transportation because of their capabilities of converting electrical/chemical energy to mechanical power at high efficiencies and reducing tailpipe emissions significantly compared to ICE-powered vehicles. Other advantages such as near-instant torque, reduced noise, less maintenance, and smooth operation benefited from fewer mechanical parts make it an attractive option to replace the existing fleet of conventional ICE-powered vehicles.

Overall, EVs can be categorised by four types: Battery Electric Vehicles (BEVs), hybrid Electric Vehicles (hEVs), Plug-in Hybrid Electric Vehicle (PHEVs), and Fuel Cell Electric Vehicle (FCEVs)[1]. BEVs account for a significant portion of the EV market, given its zero-tailpipe emission and high efficiency. However, like any other emerging technology in the early stage, BEVs come with various shortcomings, such as high upfront purchase cost, long charging time, insufficient charging infrastructure, and so on. An online survey study conducted by Edbue, *et al.* (2017) in the USA found that almost 50% of the participants in the survey were concerned with the high upfront cost, followed by range anxiety and the 'technology', which limited the uptake of EVs during the early adopter phase. These concerns worked against consumers switching from ICE-powered transport to EVs. Hence, policy interventions are deemed necessary to resolve the misconceptions of EVs in order to accelerate their uptake. Discrete choice experiments were incorporated in a comprehensive EV purchasing survey in New South Wales, Australia, in 2018 to elicit preferences for EVs under hypothetical scenarios with various government interventions. The research findings revealed that consumers were not so attracted by *rebates on parking fee*, but they were quite sensitive to *charging infrastructure support with levy*. For instance, consumers were willing to pay additional \$1.58 in levy for 1km shorter distance between adjacent charging stations. Such information provided valuable reference for policy making and infrastructure planning to promote EV uptake (Perez *et al*., 2019).

Although BEVs are considered as an environment-friendly transport mode, the question as to whether they are 'truly' a green alternative to ICEs depends on the electricity mix used to power the vehicles. Countries that are heavily reliant on fossil fuels for electricity generation may not be able to enjoy the environmental benefits of EVs (Rangaraju *et al.*, 2015). A reduction in CO_2 emissions from the adoption of BEVs depends on the extent to which electricity is generated from renewable sources. Since BEVs rely entirely on electricity, the fossil fuels used in the electricity generation mix could lead to negative effects on the environment. Ongoing research has found that FCEVs, powered directly by hydrogen, commonly known as Hydrogen Electric Vehicle (HEVs)[2], could be another silver-bullet for overcoming the environmental concern. HEVs run on electric motors powered by a fuel cell, where a Polymer Electrolyte Membrane (PEM) separates the compressed hydrogen stored in the vehicle into hydrogen ions and electrons with the aid of a catalyst. The electrons are then used to power the vehicle while the hydrogen ions combine with oxygen to form water, which is the only known non-toxic exhaust from HEVs. Globally, hydrogen is widely produced from Steam Methane Reforming (SMR) of natural gas, making up to approximately half of the total hydrogen supply, followed by pyrolysis, gasification of coal and water electrolysis from renewable power production sites (Muradov and Veziroğlu, 2005). Combined with high-energy efficiency and zero-tailpipe emissions, HEVs are considered as a promising alternative

[1] BEVs – Fully powered by battery present in the vehicle; completely reliant on electricity.
hEVs – Powered by petrol/diesel and battery; battery recharged only through regenerative braking.
PHEVs – Powered by petrol/diesel and battery; battery recharged by plug-in external electricity;
FCEVs – Powered by fuel cell instead of battery to power the electric motor.

[2] Note: HEVs refer to Hydrogen Electric Vehicles (HEVs) in the context to distinguish from hybrid Electric Vehicles (hEVs).

to replace the existing ICE fleet. Nonetheless, several technical challenges and economic concerns are embedded in the use of hydrogen due to its low power density and high cost in production.

To compare different types of EVs and to determine the right type(s) for a local market based on its electricity generation mix, vehicle uptake and transport emission targets, a diversity of studies have been conducted to analyse energy consumption and greenhouse gas (GHG) emission. A basic Well-to-Wheel (WTW) analysis which considered the fuel-cycle on buses carried out by Jwa and Lim (2018) showed the advantages of electric buses over diesel buses in terms of energy use and emissions. Onn *et al.* (2017) illustrated the long-term economic and environmental benefits of EVs over conventional vehicles. However, those studies did not consider the change of vehicle market in the future and the driving range of EVs. Orsi *et al*. (2016) conducted a WTW analysis to estimate the energy use, CO_2 emission, and economic cost for five countries with different vehicle types based on vehicle run simulation. They considered the vehicle run for only one cycle of vehicle operation and given fixed distance. However, energy consumption did not increase linearly with driving range in practice. A more elaborate and intricate study of the environmental impact of EVs while taking into account electricity trading between states of European Union showed 50%-60% GHG savings (Moro and Lonza, 2018). A study by Kosai *et al.* (2018) showed the impact of vehicle size and material on energy consumption with consideration of a single fixed driving distance, which limited the accuracy of results since the variation of distance plays an important role in calculation of energy consumption and emissions. A WTW analysis by Campanari, *et al.*, Manzolini and De la Iglesia (2009) of BEVs and FCEVs showed that BEVs were efficient only for a limited driving range since travelling longer distance required larger battery capacity and heavier/bigger battery. Svensson *et al.* (2007) applied the WTW method to analysing the impact of electricity mix in hydrogen production and directly powering the EVs. Hoffrichter *et al.* (2012) studied the role of hydrogen as an energy carrier for heavy traction application and found the natural gas pathway as the least emitting of the hydrogen production methods. Yazdanie *et al.* (2016) generated similar results based on passenger vehicles and showed that natural gas hydrogen production was the only pathway for minimising energy use, emissions and costs simultaneously. More recently, Kim *et al.* (2020) concluded that changes in future vehicle markets was an important factor in determining investment strategies in South Korea.

Although a number of studies have adopted the WTW approach for the estimation of energy consumption and/or CO_2 emission of EVs, none has considered varying driving distance, which is an important factor in determining energy consumption, CO_2 emission and vehicle weight, especially for BEVs. Another limitation of the above-mentioned literature is that most WTW research has only considered different levels of electricity mix rather than the automobile market composition of different vehicle types. To clarify the extent to which EVs could help reduce GHG emissions, different vehicle markets with various EV uptake strategies in different countries must be considered. This paper, motivated by these empirical gaps aforementioned, aims to investigate the viability of EVs in the Australian and New Zealand Light Duty Vehicle (LDV) markets, by comparing different types of vehicles, including ICEs, BEVs, PHEVs and HEVs, in three stages. First, energy consumption and emissions are estimated using a standard driving cycle with varying speed profile. Second, the cycle is repeated for different driving distances. Third, the electricity mix of the two countries is considered as a source of power for EVs and in the production of hydrogen. Finally, energy consumption and emissions through to the year 2050 are estimated using a vehicle uptake projection model. WTW methodology is employed in this study to analyse energy consumption and emissions by different types of vehicles, which will provide insights into the types of EVs that would benefit the environment based on the electricity mix and current LDV market in a particular country, and offer valuable information for policy interventions to accelerate uptake of EVs.

The reminder of this paper is structured as follows. Section 2 describes the WTW methodology and corresponding data required. Section 3 shows the WTW analysis results. Section 4 develops a vehicle uptake model which provides the basis for estimating emissions from the transportation sector through 2050. The paper concludes with a summary of results and implications to support policy making in Section 5.

2. Methodology

The WTW model includes the total primary energy use associated with the production of fuel to each unit of energy consumed at vehicle wheels. Given the entire supply chain of fuel sources, the model tracks not only the emission from the vehicle but also identifies the impact on primary energy production and the broader economy. A typical WTW model consists of two parts: Well-to-Tank (WTT) and Tank-to-Wheel (TTW) analysis. WTT analysis estimates energy consumption and emissions associated with the production, processing and transportation of fuel to vehicle, which are measured in terms of kWh expended/kWh of energy required and CO_2/kWh, respectively. TTW analysis accounts for the conversion of fuel in the vehicle to power the car based on its driving profile. Energy expended in the vehicle run is measured in kWh/given distance and emissions are measured in terms of CO_2 per km for different driving distances based on their speed profile running on the Worldwide harmonized Light vehicles Test Cycles (WLTC). By integrating both parts, a complete WTW analysis calculates energy use and emissions produced. The overall methodology is summarised in Fig. 1, and a complete list of glossary and mathematical notations throughout this paper can be found in Table 1.

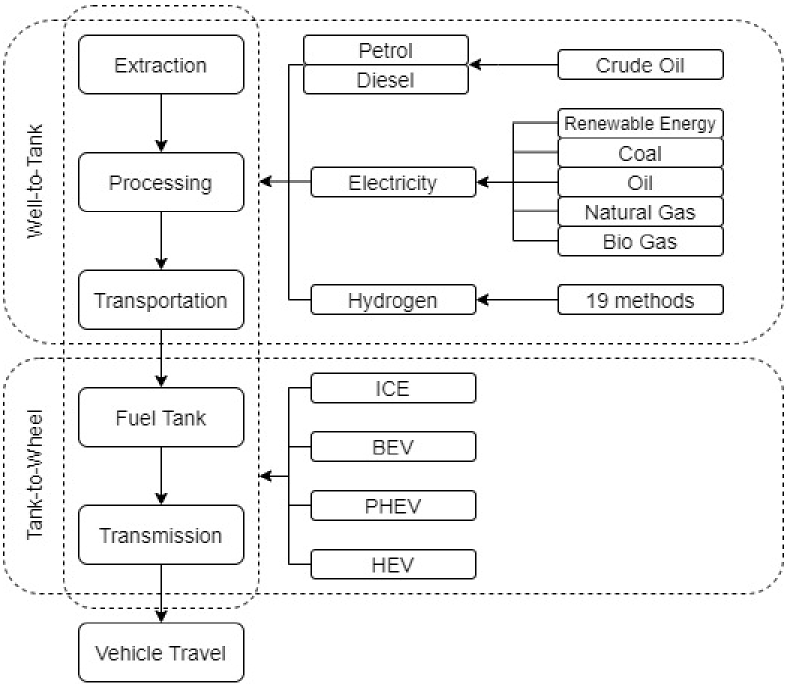


Fig. 1 The framework of WTW analysis

Table 1

List of glossary and notation used in this study.

Glossary		Notation	
BEVs	Battery Electric Vehicles	P_{total}	Total power required at wheels
BMS	Battery Management System	P_{acc}	Power required for acceleration
EB	Electric Bus	P_{ad}	Power required to overcome air drag
EV	Electric Vehicle	P_{roll}	Power required to overcome rolling resistance
FCEV	Fuel Cell Electric Vehicle	P_{inc}	Power required to overcome an inclination
GHG	Green House Gas	m	Mass of vehicle
HEVs	Hydrogen Electric Vehicles	v	The velocity of vehicle
ICE	Internal Combustion Engine	a	Acceleration of vehicle
IEA	International Energy Agency	f_{rot}	Rotational inertia coefficient
LCA	Life Cycle Analysis	c_w	Coefficient of air drag
LDV	Light Duty Vehicle	f	Coefficient of rolling resistance
PEM	Polymer Electrolyte Membrane	A	The frontal area of vehicle
PHEVs	Plug-in Hybrid Electric Vehicles	g	Acceleration due to gravity
SMR	Steam Methane Reforming	ρ	Density of air
TTW	Tank-To-Wheel	ϕ	The angle of inclination/slope of road
WLTC	World Harmonized Light Vehicles Test Cycle		
WTT	Well-To-Tank		
WTW	Well-To-Wheel		

2.1. Research scope

From an Oceanian perspective, this research focuses on local vehicles markets in Australia and New Zealand with consideration of EVs (BEV, HEV and PHEV) and the conventional ICE-powered vehicles. The drivetrain layout of different types of vehicles is shown in Fig. 2.

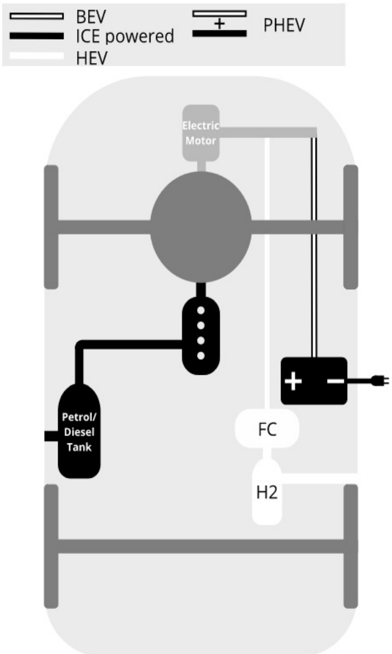


Fig. 2 Drivetrain layout of different types of vehicles (FC - Fuel Cell, H2 - Hydrogen Tank)

BEVs are powered entirely by the charge stored in the battery. Among various battery options for BEVs, such as lead-acid, Nickel Metal Hydride (NiMH) and Lithium-ion (Li-ion), Li-ion battery is considered as the best choice due to its high energy and power density, long life span, and environmental friendliness (Lu *et al.*, 2013), which is used on PHEVs as well. PHEVs are powered by both diesel/petrol and battery based on the speed profile and the Battery Management System (BMS), which is used to switch between the two sources (Song *et al.*, 2017). HEVs run on electric motor powered by a fuel cell where a PEM separates the compressed hydrogen stored in the vehicle into hydrogen ions and electrons with the help of a platinum catalyst (Delucchi, 1992). Only the PEM-based HEVs are considered in this study given its high practicality and efficiency compared to other methods (Campanari*et al.*, 2009). We only consider the direct supply of hydrogen to HEVs either in liquid or gaseous form owing to the intricacies of the supply chain and components involved in energy conversion. A conventional ICE running on gasoline is included for comparison and evaluation. In addition, regenerative braking system is considered to be used in vehicles to improve efficiency[3]. A separate battery pack is assumed to be installed in HEVs to store the power generated through regenerative braking. Although it might seem valid to adopt the regenerative braking system, the battery adds extra weight to the vehicle, which would consume additional power to carry the load. The validity of the system will be checked through the vehicle run simulation in the subsequent sections. PHEVs are considered only with regenerative braking since it has been widely used in the market. All vehicle types covered in this study are shown in Fig. 3 as follows.

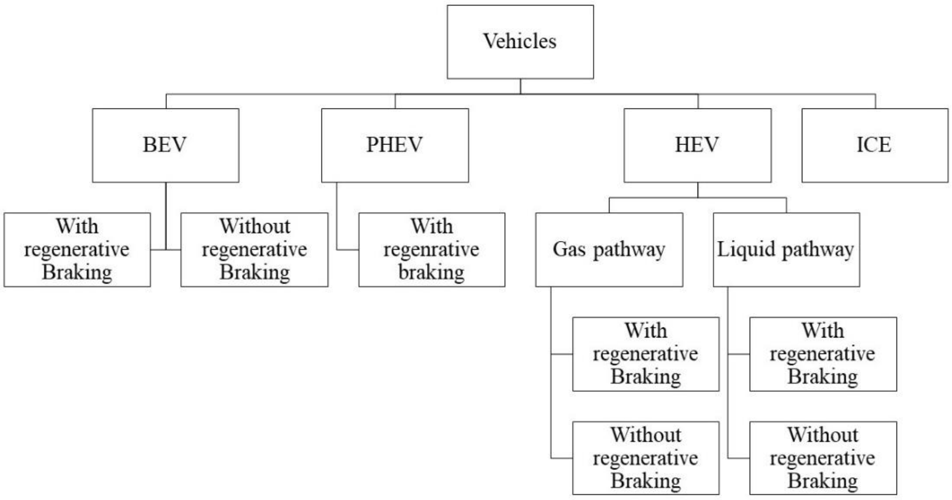


Fig. 3 Vehicle types covered in this study

2.2. TTW Analysis

2.2.1. Vehicle run simulation

Each of the four types of vehicles is assumed to run following the WLTC driving cycle in simulation. This driving cycle is used as a benchmark with a standard speed profile for all types of vehicles with intermittent starts, stops and braking as defined in UNECE (2014). Among a diversity of driving classes, Class 3b[4] is chosen for the vehicle run simulation as it covers the speed profiles of all types of vehicles in this study, as shown in Fig. 4.

[3] Regenerative braking charges a battery by converting the conserved kinetic energy during vehicle braking into electrical energy.
[4] Class 3 represents light duty vehicles and Class 3b denotes the vehicles with a maximum speed higher than 120 kmph.

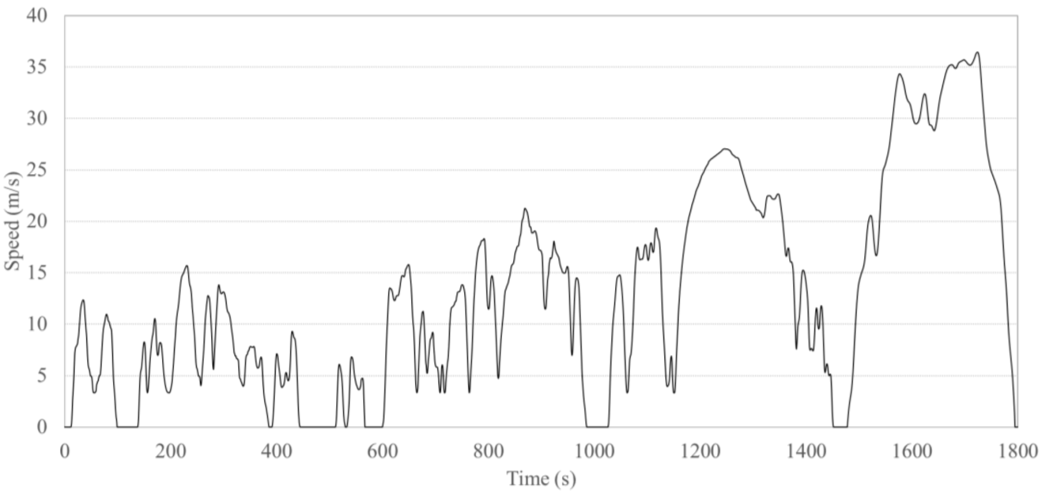


Fig. 4 Speed profile generated from WLTC driving cycle

2.2.2. Energy Consumption

With speed profile, the energy required for each vehicle depends on the drivetrain used in each type of vehicle. The overall energy requirement at the vehicle wheels is governed by the formulae below (Bauer, 1996).

$$P_{acc} = m \times v \times a \times f_{rot} \quad (1)$$

$$P_{ad} = \frac{c_w \times A \times \rho \times v^3}{2} \quad (2)$$

$$P_{roll} = f \times m \times g \times v \times cos\,\theta \quad (3)$$

$$P_{inc} = m \times g \times v \times sin\,\theta \quad (4)$$

$$P_{tot} = P_{acc} + P_{ad} + P_{roll} + P_{inc} \quad (5)$$

wherein $f_{rot} = 1.1$, $c_w = 0.29$, $f = 0.011$, $A = 2.27m^2$, $g = 9.81\,m/s^2$, $\rho = 1.225\,kg/m^3$, and $\theta = 0^{\circ}$. In this study, the slope of the road is assumed to be zero. The mass component of the vehicle is the sum of curb mass (excluding fuel storage) and mass of fuel storage, and the fuel tank/battery required to power the car is added to the curb mass to obtain the overall weight of the vehicle. The weight of the storage in-turn depends on the power demand at the wheel. The curb mass of an EV and ICE vehicle is assumed to be 1380 kg and 1399 kg, respectively[5], which is assumed to be the base mass of the car. An iterative solving method based on Eq. (1)-(5) is used to find the optimal vehicle mass and corresponding energy demand based on the driving cycle. Vehicle mass depends on the energy source used to power the car as each type may include different drive trains, batteries, fuel cells, fuel tank, and so on.

Batteries usually have lower energy density compared to other kinds of fuels. According to Placke *et al.* (2017), the specific energy of a battery is approximately equal to 0.0037 kg/Wh and an energy density of 1000 Wh/l. Thus, it would require more fuel or bigger battery for a given distance compared to other fuel sources. Naturally, BEVs would be generally heavier than other types of vehicles. Moreover, to increase battery capacity, vehicles would need more

[5] The total mass of a 2013 model 30kWh Nissan Leaf hatchback is 1500 kg (Used 2013 Nissan LEAF Features & Specs, 2019). The mass of a 30 kWh battery is 120 kg. Thus, the kerb mass of an electric vehicle with electric drive train is 1380 kg. The mass of a 2013 model 30kWh Nissan Leaf without the drive train is 1300 kg (60 kg for e-components and 20 kg for inverter). When including the mass of ICE, gear and exhaust (69 kg, 20 kg and 10 kg resp.), the kerb mass of an ICE vehicle is 1399 kg (Konrad *et al*., 2010).

space to accommodate additional battery units. Therefore, a corrective mass of 15% is added to take the physical expansion of the car into account (Campanari *et al.*, 2009).

For HEVs, although the specific energy of H_2 is high, the energy density and volumetric density remains low at 0.003 kWh/l and 0.09 kg/m^3, respectively (Reuß *et al.*, 2017). Furthermore, it would require compression at 700 bar to store H_2 in the vehicle. Thus, 1 kg of hydrogen contains 33.3 kWh of energy, which is higher than its BEV counterpart. Based on the compression ratio, the size of the fuel tank increases considerably to 13.50 kg_{tank}/kg_{fuel} and 17.54 kg_{tank}/kg_{fuel} for liquid and gaseous hydrogen, respectively (Campanari *et al.*, 2009).

The PHEV considered in this study is a diesel hybrid, and the ICE is a gasoline-powered vehicle. The energy density of diesel and petrol is 10 kWh/l and 9.1 kWh/l, with a volumetric density of 850 kg/m^3 and 780 kg/m^3, respectively. If regenerative braking is considered, the weight of a Li-ion battery is to be considered for recharging the vehicle. For the purpose of simulation, the speed range below which the PHEV runs on the battery is set to 25 m/s, and above this speed the vehicle runs on its ICE (Williamson, 2007).

Fig. 5 shows the consolidated drivetrain efficiencies of different types of vehicles derived based on Karlsson and Kushnir, (2013) and de Pablo *et al.* (2016). According to the efficiency values and the iterative solving method, the amount of energy required to run over the driving cycle (TTW) can be calculated.

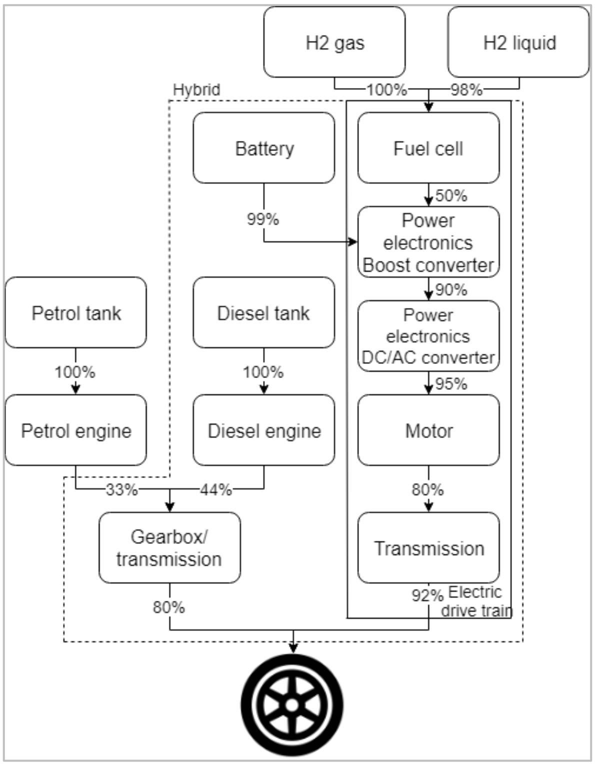


Fig. 5 The drivetrain efficiencies of different vehicle systems with their efficiency values

2.2.3. Emissions

There is no tailpipe emission from BEVs. In this study, we consider HEVs where H_2 is directly supplied to the vehicle and is stored in tanks. Thus, the tailpipe emission from HEVs is zero. Emissions from the combustion of gasoline and diesel are calculated using the customizable data sheet provided by the Minnesota Pollution Control Agency (Minnesota Pollution Control Agency, n.d.), and the amount of CO_2 generated from the combustion of gasoline and diesel is 0.240 kg of CO_2/kWh and 0.252 CO_2/kWh, respectively.

2.3. WTT Analysis

This section calculates energy consumption and emissions involved in the production/extraction (Well), processing, and transportation of the final fuel to the fuel tank (Tank) required to power the vehicles. Based on the types of vehicle considered, the production supply chain of the fuel varies. Fuel/energy sources used include crude oil, hydrogen and electricity.

2.3.1. Energy Consumption

(1) Crude oil

The amount of energy expended to produce gasoline, having an energy equivalent of 1 MJ, requires 18% additional energy to supply it. This energy consumption includes energy consumed in crude oil exploration, extraction, transporting crude oil to the refinery, refining and delivering the refined gasoline to the gas stations. Thus, the overall efficiency of the process involved in the production of gasoline is 84.7%. An additional 13% of energy is required to supply the market with 1 MJ of diesel equivalent, an efficiency at 88.4%. This number is comparable to the 1.2 MJ of primary energy input required to produce 1 MJ of diesel equivalent based on the findings in Sheenan *et al*. (1998).

(2) Hydrogen

Hydrogen is the most abundant element in nature but is not present in its natural state as elemental H_2. Hydrogen can be produced from different sources, including zero-emission power sources and fossil fuels. The overall energy consumption and the emissions involved in the production process depend on the method used to produce H_2. According to Dincer and Acar (2015), we can divide H_2 production methods into three categories based on the primary sources, as shown in Fig. 6, and the corresponding efficiency values of these processes are shown in Fig. 7. Each production method shown in Fig. 7 is given a number (1 to 19) for succinct illustration in other figures, such as Fig. 9 and Fig. 10.

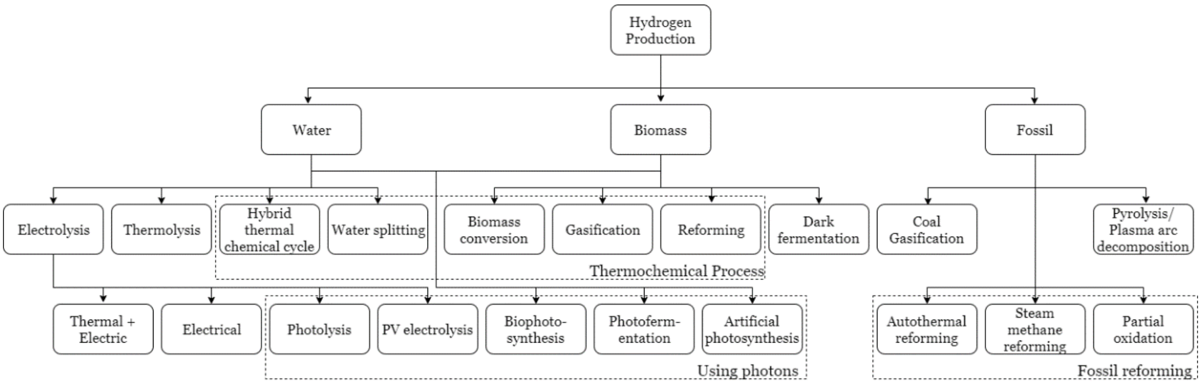


Fig. 6 H_2 gas production methods based on primary material used

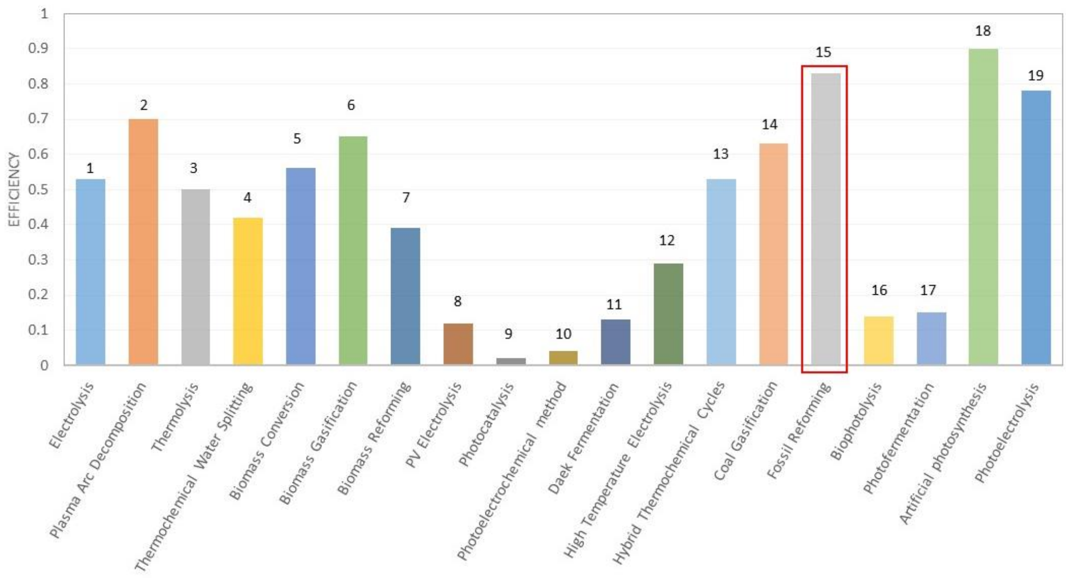
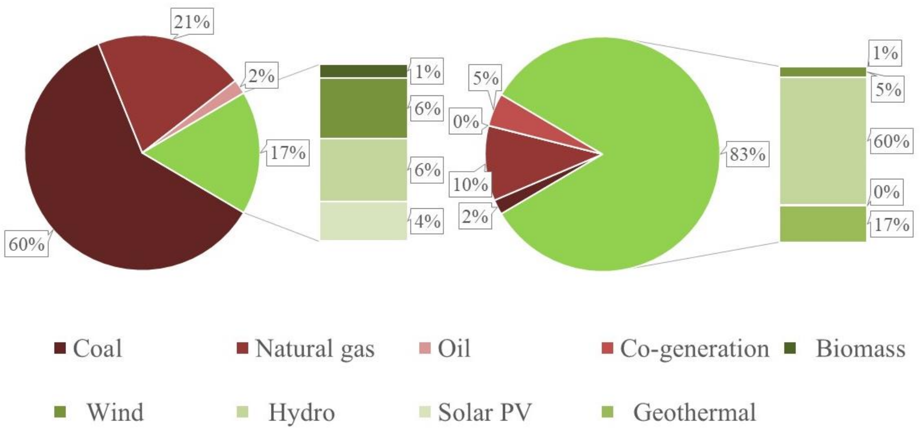


Fig. 7 Efficiencies of different H_2 production methods

Natural gas SMR is the most commonly used method to produce H_2 due to its high efficiency, comparatively lower energy consumption and practicality (Nikolaidis and Poullikkas, 2017; Holladay *et al.*, 2009). While auto thermal reforming and partial oxidation is also a part of fossil reforming, which requires pure oxygen supply to produce H_2 and hence increases the complexity and cost of the process. Although other methods are more efficient, the relevant capital cost, emissions, or the raw materials required to produce H_2 are more significant. For example, artificial photosynthesis has the potential to produce H_2 by splitting H_2 and O_2 from water molecules. However, since it is in the early stages of R&D, the high capital cost involved in the method hinders it becoming an economically viable option at current stage. Coal gasification is an economical and technically feasible option considering the availability of a large number of coal reserves. However, it is not environment friendly since it is one of the highest emitters of CO_2. Hence, only the SMR technology is considered for H_2 production in this paper.

Once H_2 is produced, it can be transported either in gaseous or liquid form. Gaseous hydrogen must be compressed to 60 bars for supplying it through pipelines or up to 200 bar for transport by truck. However, hydrogen still escapes, which leads to losses. On the other hand, liquid hydrogen has nearly twice the energy density at 700 bar, but it needs to be stored in a special cryogenic tank to prevent losses. Relatively, distribution losses might be lower, but the energy required for liquefaction is significantly higher. According to Zheng *et al*. (2012), a standard piston-type mechanical compressor would require 2.21 kWh of energy to compress 1kg of H_2 up to a pressure of 77 MPa or 770 bar, but liquid hydrogen with higher energy density would need 15.2 kWh to compress 1kg of H_2-equivalent due to its low boiling point (252.87°C). In addition, the tank weights for storing H_2 in its liquid and gaseous forms are 13.50 kg_{tank}/kg_{H2} and 17.54 kg_{tank}/kg_{H2}, respectively (Campanari *et al.*, 2009). The total energy used to produce the necessary electrical power for vehicle battery depends on the electricity generation mix since each method has different efficiency values. Utilizing the Australian and New Zealand electricity generation data collected from Department of Environment and Energy (2019) and MBIE (2019) respectively, Fig. 8 shows the contributions of different sources to the overall electricity mix of the two countries.



(a) Australia (b) New Zealand

Fig. 8 Electricity mix in Australia and New Zealand in 2018

The New Zealand electricity mix is dominated by renewable power, with hydro (60%) forming a significant portion of the electricity mix, followed by geothermal (17%), natural gas (10%), and wind (5%). In contrast, the Australian electricity mix is dominated by coal (60%), followed by natural gas (21%), hydropower (6%) and wind (6%). Hence industries or sectors that depend on electricity as their primary energy source would be associated with higher emissions in Australia.

Efficiency values of each power generation method from the extraction of raw materials to processing, transportation of the processed materials to the power station, and finally conversion of the primary energy source to the transformation of electricity are given in Table . The amount of energy required to supply the power for EVs is based on the efficiency values and generation mix.

Table 2

Efficiency values of different power production methods.

Power plant	**Stages of loss**				**Final Efficiency**	**Source**
	Extraction	Processing	Transport	Power Plant		
Renewable power source[6]	100%	100%	100%	100%	100.0%	
Coal	86.5%	94.04%	99%	40%	32.2%	Wang *et al*. (2015); Baruya, (2012)
Natural gas	92%	94%	94%	46%	37.3%	Waller *et al*. (2014); Wang *et al*. (2015)
Oil	93%	82.5%	98%	40%	30.0%	IEA (2009)
Biogas	51%		86.5%	75%	33.0%	Yoshida *et al*., *(2003);* Pöschl *et al*. (2010)
Co-generation	92%	94%	94%	60%	48.7%	Yoshida *et al*., (2003)

[6] For renewable power source, the consumption of primary fuel is zero, considering the availability of the sources is assumed to be infinite and hence losses do not affect the evaluation except during transmission.

2.3.2. Emissions

(1) Crude oil

The petroleum supply chain is one of the largest emitters of GHG, with most of emissions attributed to the extraction of the raw materials, refining of crude oil and transportation of fuels. According to Simpson (2005), the production of petrol and diesel from crude oil extraction, production of fuel, and distribution generates 256.9 gCO_2/kWh and 250 gCO_2/kWh, respectively.

(2) Hydrogen

Of the different hydrogen production processes, fossil based H_2 production generates the highest emissions. Biomass-based methods emit the highest amount of SO_2 into the atmosphere. Water-based thermochemical processes and photonic processes are the least toxic. Although the environmental benefits are far better with water based H_2 production methods, the efficiency of these processes is too low to make it economically viable for production in a large scale. According to Dincer and Acar (2015), the emission values are outlined in Fig. 9. Fossil reforming shows comparatively high emissions but at present, it is the most economically viable option. Only fossil-based reforming is considered in this study due to its high efficiency and practicality.

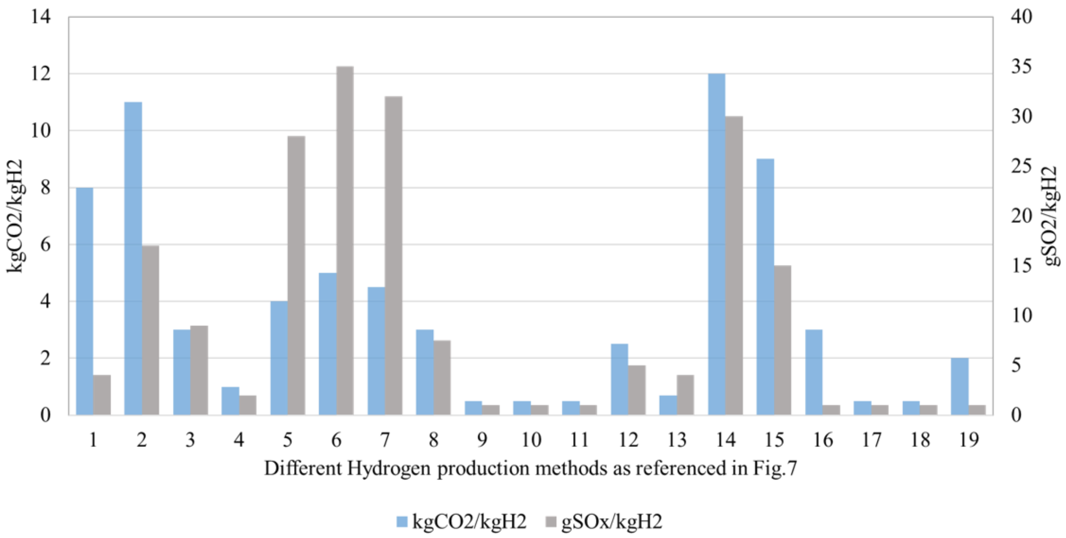


Fig. 9 Emissions produced from different H_2 production methods

(3) Electricity

Emissions associated with each electricity production method vary. The discharges and related energy use are highly country specific. Multiple types of primary fuels and their estimated emissions are shown in Table 3.

Table 3

CO_2 emissions from different types of primary fuels.

Primary fuel	Coal	Natural gas	Co-gen	Oil	Biomass	Geothermal
CO_2 (kg/kWh)	0.918	0.595	0.44	0.739	0.055	0.007

Due to a lack of data on Australian and New Zealand's electricity production and the associated emissions, we estimate of relevant CO_2 parameters based on a comprehensive literature review. The detailed data sources and calculation are shown in Table 4.

Table 4

Detailed data sources and calculation for estimation of CO_2 parameters.

Primary fuel	Power plant	Emissions (CO_2) - kg/kWh			CO_2 - kg/kWh	Source
		Extraction / production	Transport	Power production		
Coal	Coal-fired power plant				1.18	Mazandarani *et al.*,(2011); Mahlia (2002)
		0.09		0.95	1.94	Turconi *et al.* (2013)
					0.98	Santoyo-Castelazo *et al*. (2011)
		0.016	0.0156	0.886	0.918	Hondo (2005)
					0.851	Chang *et al.* (2015)
	Super-critical power generation	0.022	0.026	0.776	0.826	Hardisty *et al.*,(2012)
	IGCC	0.05		0.725	0.775	Turconi *et al.* (2013)
Coal – Final estimated value					*0.918*	
Natural gas	Steam turbine	0.1		0.38	0.48	Turconi *et al.* (2013)
					0.412	Santoyo-Castelazo *et al.* (2011)
	OCGT	0.07	0.03	0.54	0.64	Hardisty *et al.* (2012)
		0.098	0.019	0.477	0.595	Hondo (2005)
	Gas turbine				0.664	Mazandarani *et al.* (2011)
Natural gas – Final estimated value					*0.595*	
Co-gen	CCGT				0.409	Mazandarani *et al.* (2011)
		0.05	0.02	0.37	0.44	Hardisty *et al.*(2012)
		0.084	0.016	0.407	0.508	Hondo (2005)
Co-gen – Final estimated value					*0.44*	
Oil	Steam turbine				0.575	Mazandarani *et al.* (2011)
					0.709	Santoyo-Castelazo *et al.* (2011)
		0.028	0.006	0.704	0.739	Hondo (2005)
	Diesel engine				0.813	Mazandarani *et al.* (2011)
		0.02		0.72	0.74	Turconi *et al.* (2013)
Oil – Final estimated value					*0.739*	

Biomass	Coal + Biomass co-firing			0.043	Bhat and Prakash, (2009); Spath and Mann (2004)
		0.01	0.045	0.055	Turconi *et al.*(2013)
	IBGCC			0.178	Bhat, & Prakash, (2009); Carpentieri *et al.*(2005)
		0.04	0.001	0.041	Turconi *et al.* (2013)
	Biogas cogeneration			0.078	Bhat and Prakash, (2009); Chevalier and Meunier (2005)
	Coal + Straw			0.037	Bhat and Prakash, (2009); Hartmann and Kaltschmitt (1999)
	Coal + Wood			0.035	Bhat and Prakash, (2009); Hartmann and Kaltschmitt (1999)
	IGCC combined cycle			0.11	Bhat and Prakash (2009); Rafaschieri *et al*. (1999)
	Direct combustion	0.054	0.045	0.099	Turconi *et al*. (2013)
Biomass – Final estimated value				*0.055*	
Geothermal				0.009	Hondo (2005)
				0.002	Martín-Gamboa *et al*. (2015)
				0.006	Atilgan and Azapagic (2016)
				0.035	Karlsdottir *et al.* (2010)
				0.062	(NZGA, 2019)
Geothermal – Final estimated value				*0.007*	

Zero-emission from renewable power sources is assumed, except for geothermal power plants[7]. Although the emission from geothermal is considerably less than fossil-fired power production, it is still part of the overall GHG emission in atmosphere (Van Campen, 2020). In general, emissions from geothermal power production are from two sources: the power production process and the natural release of CO_2 from geothermal systems, and the latter forms a significant portion of the emission.

[7] Note: Only the power production process and operation in WTT analysis are considered. The emissions associated with construction and decommissioning are not covered in this study.

3. WTW analysis results

3.1. Energy consumption

For HEVs, the amount of energy consumption is one of the lowest in the case of fossil reforming through SMR, partial oxidation, or autothermal reforming. The amount of energy required to produce 1kg of H_2 using different methods, which includes the energy expended in compressing and phase-shifting H_2, as shown in Fig. 10. The amount of energy required to produce and supply liquid H_2, denoted as H2 (l), is higher than its gas counterpart, represented by H2 (g). This is due to the high compression pressure required to transport the liquid H_2.

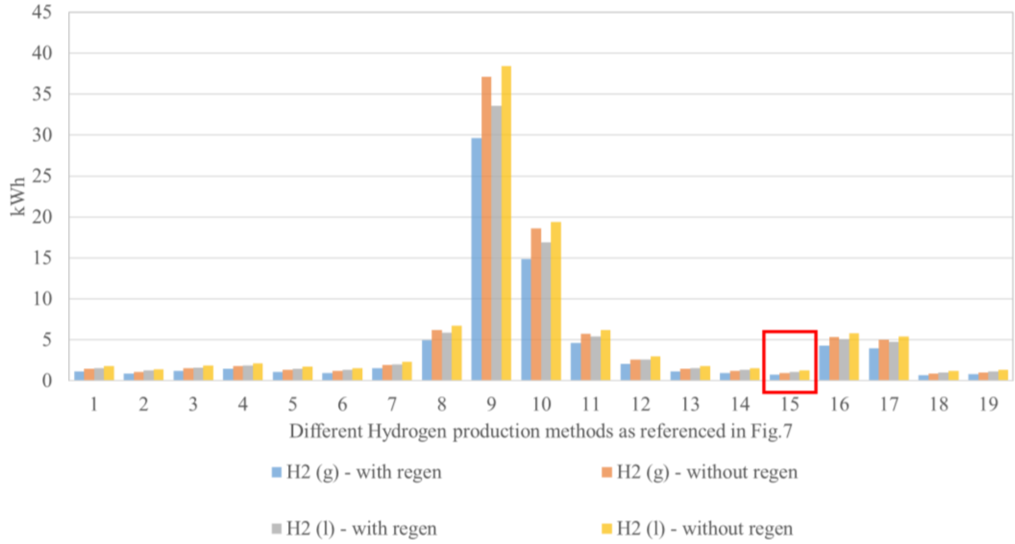


Fig. 10 WTT energy consumption for HEV (1km driving cycle)

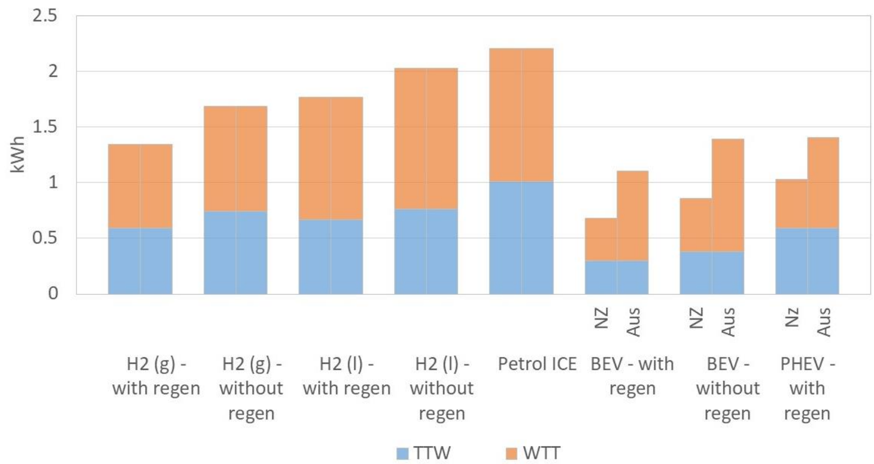


Fig. 11 WTW energy consumption for different types of vehicles (1km drive cycle)

Fig. 11 shows the WTW energy consumption for different types of vehicles in a driving cycle normalized to 1km. The amount of TTW energy consumed for BEVs is the lowest, followed by PHEVs and then HEVs. The WTT energy consumption varies between the two countries because the amount of energy required for BEVs and PHEVs depends on the electricity generation mix directly. Due to the fossil-dominated electricity mix in Australia, the energy expended in producing the required energy is higher. On the other hand, electricity generation is dominated by renewable sources in New Zealand, which results in lower energy consumption. According to Eq. (3) and (4), the amount of energy consumed is determined by the relative acceleration and the velocity of vehicle. Therefore, the high TTW energy consumption is due to the frequent acceleration and deceleration in the driving cycle. Although liquid hydrogen has higher energy content than gaseous hydrogen, the weight of tank required to store liquid hydrogen and the losses due to escape are more significant than those of gaseous hydrogen. Therefore, the TTW energy consumption of liquid and gaseous hydrogen are almost the same given the hydrogen production methods.

Moreover, it is evident from Fig. 11 that the provision of regenerative braking indicates a positive impact on energy consumption considering the energy recovered during braking or deceleration is stored in a battery to power the car when required. Although regenerative braking causes the addition of battery pack to the overall vehicle weight, for a short distance, the energy stored and recovered through regenerative braking far exceeds the limitations of the mass added, making the vehicle more energy efficient. Diesel-PHEVs with regenerative braking are an economical option due to the optimal switching between the electric motor and the combustion engine. On the contrary, petrol ICEs show the highest WTW energy consumption as the energy required to extract and process the crude oil to produce fuel is in a high level.

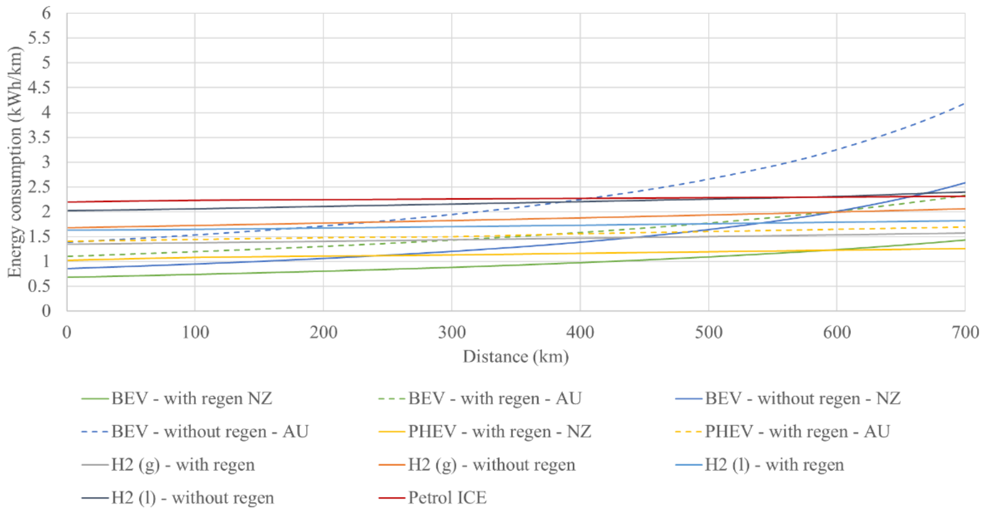


Fig. 12 WTW energy consumption based on driving distance

Fig. 12 presents the energy consumption for different types of vehicles based on driving distance. The energy requirement per km of BEVs increases with the driving distance because a bigger battery pack is required to secure enough power for long-distance driving, increasing vehicle weight and reducing energy efficiency. Regeneration also plays a significant role in attaining energy efficiency considering that the additional power stored in the battery through regenerative braking is higher than the energy consumption in overcoming the additional weight of battery. Among multiple types of vehicles, the energy consumption of a BEV with regeneration running on the electricity mix in New Zealand remains the lowest up to a distance of 600km. Beyond that distance, the negative effect (energy consumption) of the added weight exceeds the additional power supplied by increasing the battery capacity. PHEVs have a comparatively good energy efficiency following BEVs in all range of travel distances, and shows the lowest energy consumption for long-distance travel, i.e., above 600km. Given the relatively high energy density of H_2 coupled with the relatively low weight of HEVs, results in relatively low energy consumption over longer driving distance. An HEV with regeneration running on liquid H_2 is more efficient than an HEV running on gaseous H_2 without regeneration. However, since liquid H_2 has to be stored in a double-layered tank (usually cryogenic), it is not as efficient as its gaseous counterpart. Thus, in New Zealand, BEVs offer the best energy-efficient solution for driving distance up to 600km, beyond which PHEVs and HEVs become more energy-efficient solutions. For the Australian electricity mix, the energy required for BEVs with regenerative braking system is relatively low for a driving distance up to 300km, beyond which HEVs and PHEVs are more energy efficient.

3.2. Emission

Fig. 13 shows the CO_2 emissions produced from different types of vehicles running in the driving cycle, normalized for 1km. In New Zealand, BEVs offer the best option for minimising emissions. Since BEVs and HEVs do not generate any emission during the vehicle run, the emission is produced only from the production of the fuel. Considering that renewable sources dominate New Zealand electricity generation, the emission from BEVs is far less than that from other types of vehicles. In the case of Australia, the overall emission from BEVs is higher than that of HEVs, making HEVs a better option from an environmental perspective.

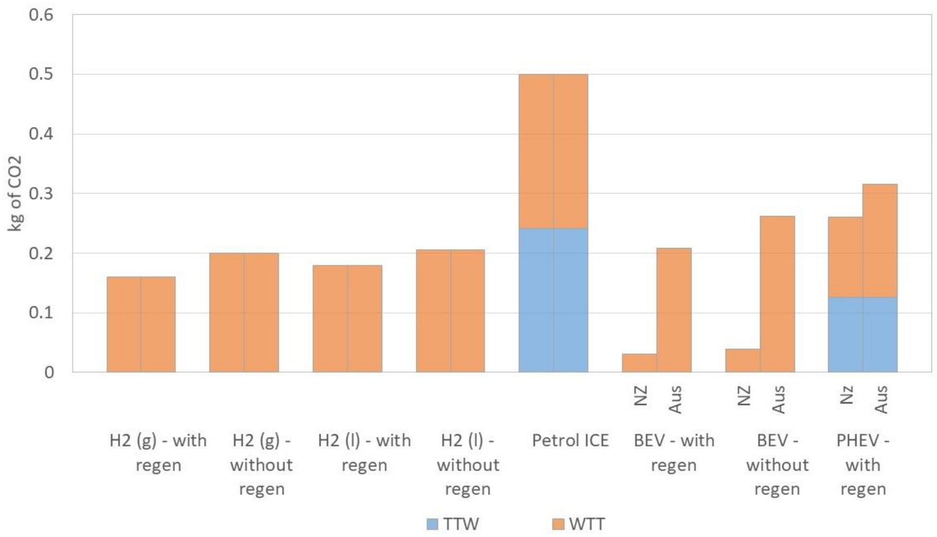


Fig. 13 WTW emissions for different types of vehicles (1km drive cycle)

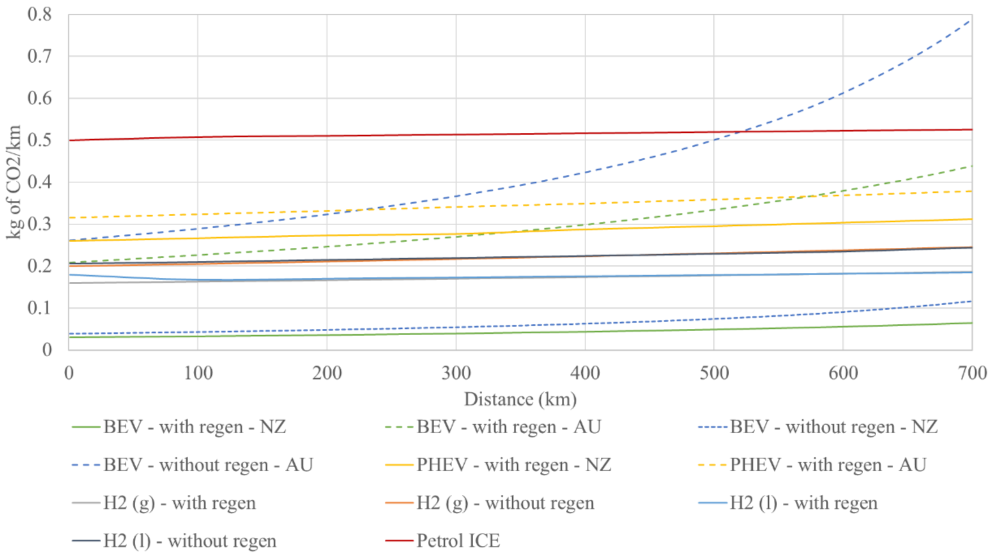


Fig. 14 WTW emission based on driving distance

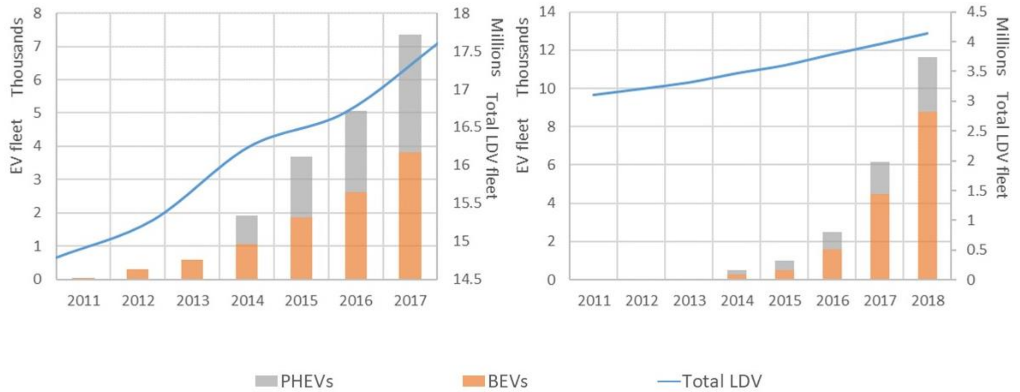
Fig. 14 shows the emissions produced by different types of vehicles based on driving distance. Emissions from BEVs remain the lowest in New Zealand, followed by HEVs, PHEVs and ICEs. Emissions from HEVs are relatively constant over all driving distances. The high energy supplied by the liquid H_2 is offset by the heavier tank required to store the fuel and the high energy needed to compress the liquid. Thus, emissions generated from the production of liquid and gaseous H_2 remains almost the same. Similar results were found by Campanari *et al.* (2009). From an emissions perspective, regenerative braking also offers benefits due to the reduction in energy consumption and independent power generation. On the contrary, emissions from BEVs in Australia remains one of the highest due to the dependence of fossil intensive electricity mix. In this case, HEVs are a superior option to mitigate emissions in Australia. As aforementioned, producing H_2 from natural gas is a better option than relying on coal for the electricity generation to supply for BEVs in Australia. Therefore, HEVs offers the best long-term solution for Australia in terms of emissions, followed by BEVs and PHEVs.

4. Projected emissions through 2050

In previous sections, energy consumption and emission are estimated based on varying driving distance following the WLTC driving cycle in simulation. To predict the future energy consumption and emission in New Zealand and Australia, EV penetration and the corresponding amounts of BEVs, PHEVs and HEVs sales in both countries need to be estimated. First, we study the global EV market. Second, an EV uptake model is developed based on the historical sales figures and targets set by the respective governments to predict the fleet growth until 2050. Finally, the predicted results of EV uptake in both countries are adopted by the energy consumption and emission model to calculate the associated energy demand and emissions in the future.

4.1. Future EV penetration

The EV penetration rate in the global market has achieved tremendous growth since 2010, and the total EV fleet surpassed 5.1 million in 2018, with a growth rate of 63% up from 2017. China is one of the biggest EV markets, making more than 45% of the global EV passenger fleet. The EV market is expected to grow exponentially in the future due to falling battery and vehicle costs, improved battery efficiency, increased driving range, more charging infrastructure, consensus on reaching the global emission targets, and increasing availability of vehicle models. Of the total sales of EVs, BEVs contributed to 64% of the entire EV fleet, followed by PHEVs and FCEVs (IEA, 2019c).



(a) Australian market (b) New Zealand market

Fig. 15 Vehicle fleet size in Australia and New Zealand

Fig. 15 shows the total Light Duty Vehicle (LDV) and EV fleet size in Australia and New Zealand between 2011 and 2018. New Zealand shows a linear growth in the total number of LDV with an exponential increase in the number of EVs from 6141 (4486 BEVs and 1655 PHEVs) at the end of 2017 to 11634 (8798 BEVs and 2836 PHEVs) at the end of 2018, almost doubling the fleet size (Ministry of Transport, 2019a). The EV fleet makes up 0.3% of the total LDV in New Zealand. Australia, on the other hand, shows a steeper increase in the total LDVs with 7341 EVs (3822 BEVs and 3519 PHEVs) at the end of 2017 (Costello, 2017; ClimateWorks Australia, 2018), making up less than 0.05% of the total fleet and 0.2% of the total LDV sales[8].

The Ministry of Transport (MoT) in New Zealand has predicted that EVs will make up to 40% of the total vehicle fleet by 2040 and 64,000 EVs will join the entire vehicle fleet by 2021 (Ministry of Transport, 2017). Deutsche Bank expects EVs to make up 100% of the new LDV sales in New Zealand by 2030 and all used import fleet by 2035 (Parkinson, 2019). Based on these estimates, EVs are expected to make up 53% of the total LDV fleet by 2040 and 90% by 2050, which is higher than the sales figures expected by the MoT. Conservative estimates show EVs completely replacing the existing ICE fleet by 2060. Similarly, a recent report on estimating EV adoption in Australia predicts EVs to account for 8% of new passenger vehicle sales by 2025 and 65% by 2050 (BITRE, 2019).

4.2. EV uptake modelling

An EV uptake model is developed based on the projections and targets set by the two countries (MoT - 40% EV by 2040 and BITRE - 65% EV sales by 2050). Based on the actual number of vehicles entering the fleet and fleet size, the fleet growth is extrapolated using a modified exponential growth model (Draper *et al.*, 2008), which is a widely used tool for scenario analysis. Specifically, Eq. 6 and Eq. 7 are used to predict the growth of EVs based on the historical sales data in New Zealand and Australia.

$$Y_t = y_t(V_{enter} - V_{exit}) \tag{6}$$

$$y_t = \frac{k}{1+e^{-k(t-m)}} \tag{7}$$

wherein V_{enter} and V_{exit} are the total numbers of vehicles entering and leaving the fleet, respectively. y_t represents the EV uptake as a percentage of total vehicle entering the fleet, k is the carrying capacity, t is the time period under consideration, and m is the factor shifting the timeline of the curve based on the first and the last year under consideration.

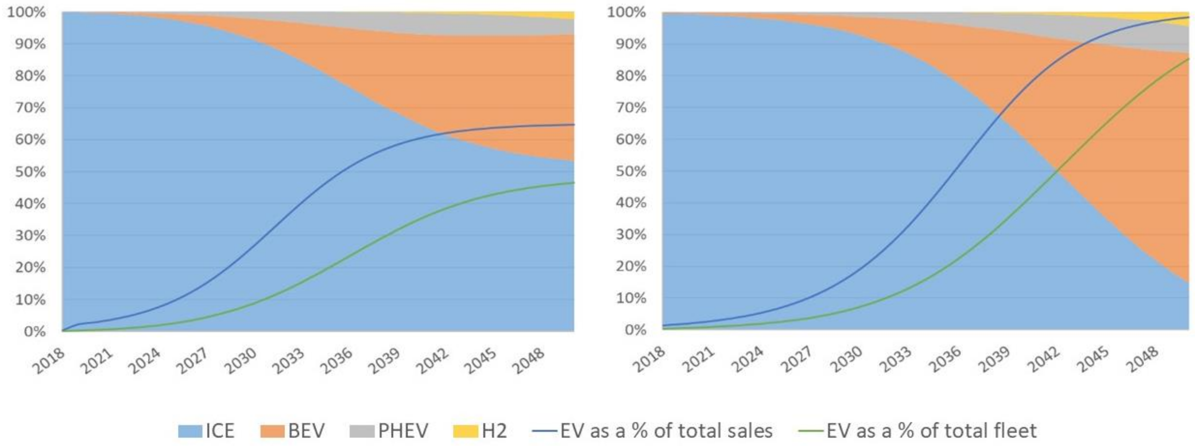
This model also takes into account the average vehicle age in New Zealand and Australia, which are 14 years and 10 years old, respectively (Ministry of Transport, 2019b; Australian Bureau of Statistics, 2019). Average fleet age is used to estimate the number of vehicles entering the fleet, leaving the fleet, and EVs entering the fleet based on the sales target set by both countries. The trip length assumed for this analysis is 500km. According to the International Energy Agency (IEA, 2019c), BEVs are expected to make up a significant portion of the EV market in the future. Based on this, we project the uptake of BEVs, PHEVs and HEVs through 2050 at 85%, 10% and 5%, respectively, to find the individual contribution of each type of vehicles towards replacing the existing ICE fleet and reducing direct and indirect emissions from the transportation sector. To reduce complexity, we assume that HEVs are equipped with regenerative braking to start entering the market from 2026. It is assumed that

[8] The actual fleet number may vary due to inconsistencies in the total EV sales data and the lack of Tesla sales figures in Australia. Approximated value has been calculated to match the data to the total sales figures.

it will take 5 years from 2020 for the commercialisation of hydrogen infrastructure to support vehicle uptake.

4.3. Resulting emissions

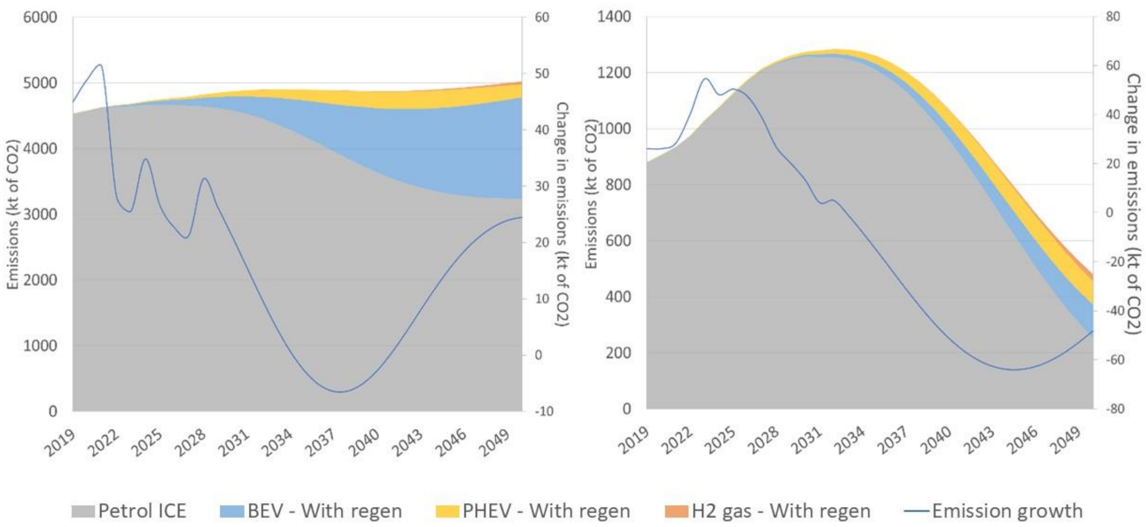
In the future, the ICE vehicle fleet will take less and less portion in the vehicle market, hence the direct emissions from transport sector are expected to reduce, making way for a low carbon transportation fleet.



(a) Australia (b) New Zealand

Fig. 16 Projected uptake of different types of vehicles

Fig. 16 shows proportions of different types of vehicles projected till the year 2050 based on sales and fleet targets. With the sales target in Australia, EVs are expected to make up to 50% of the total number of vehicles by 2050, which also takes into account that EVs make up to 8% of the vehicle sales by 2025. Overall vehicle sales are saturated at 65% based on BITRE's estimation of EV sales. New Zealand, on the other hand, is expected to have almost 90% of the total fleet made up of EVs by 2050 based on MoT's 40% EV target by 2040. Based on these estimates, projected emissions are shown in Fig. 17.



(a) Australia (b) New Zealand

Fig. 17 Total WTW emission and emission growth based on the vehicle uptake levels

With the high uptake of BEVs, emissions increase in Australia due to the high reliance on non-renewable power sources for electricity generation. Emissions decrease by a small amount through 2038 and then increase with the higher level of EV uptake. Moreover, a saturation level of 65% EV sales results in the total fleet comprising less than 50% EVs, and as a consequence, emissions increase due to high indirect emissions from electricity generation. Therefore, BEV would not be an environmentally viable option for Australia with the current electricity mix. On the contrary, the total emissions in New Zealand are expected to fall with the increasing EV uptake. Since the energy required to power EVs is mostly provided through renewable sources, emissions fall through 2050.

5. Conclusions and policy implications

This research presented a comparative study of energy consumption and emissions from HEVs, BEVs, PHEVs and ICEs in Australia and New Zealand. By applying the WTW approach, we identified heterogeneous emission profiles associated with different electricity mix and EV penetration in Australia and New Zealand. First, the WLTC driving cycle was simulated based on varying driving distance to calculate TTW energy consumption and emissions. WTT energy consumption and emissions were calculated by analysing the supply chains of different fuels, including electricity and hydrogen. Using the calculated WTW data, emissions were projected through 2050 based on vehicle sales data in Australia and New Zealand.

The analysis results suggest that BEVs offer a pathway for minimising emissions from the transport sector in New Zealand. On the other hand, HEVs minimise transportation emissions in Australia in a long run. It is also worth noting that the average driving distance plays an important role in choosing the right policy option. Moreover, our results provide empirical support for New Zealand's policy of fiscally neutral subsidy on EVs funded by tax on ICEs aimed at cleaning up the country's LDV fleet. The government proposed a discount of up to NZD $8,000 on imported EVs and hybrid vehicles in order to reduce the cost burden for consumers. At the same time, government also planned to add on a new fee of up to $3,000 on the import of vehicles with the highest GHG emissions.

The research findings are in line with Australia's National Hydrogen Strategy, where the Council of Australian Governments (COAG) Energy Council advocated development of a national hydrogen refuelling network that would lead to HEVs becoming viable in the local market. For a country with high coal dependency in their electricity mix, as opposed to New Zealand, BEVs may not be an ideal pathway for Australia due to their higher GHG emissions compared to the ICEs. Rather, an expansion of the public infrastructure support for hydrogen should be prioritised in Australia's strategy, so that the beneficial environmental effects of HEVs could be boosted.

In this study, the prediction results do not account for electricity transmission losses, which can be considered in future research. Moreover, the likely future changes in the electricity mix and the share of solar are not considered. Future research avenues will also be focused on promoting Electric Buses (EBs) based on the well-developed WTW methodologies from this paper. With the availability of relevant EB operational data and EB fleet transition plans provided by transport agencies in New Zealand and Australia, we will be able to conduct a comprehensive study for analysing low-emission alternatives in heavy duty applications thus identifying the suitable types of EBs for both countries.

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CRediT authorship contribution statement

Mingyue Sheng: Conceptualization, Writing - Original Draft. **Ajith Viswanath Sreenivasan**: Formal analysis, Writing - Original Draft. **Basil Sharp**: Writing - review & editing, Funding acquisition, Project administration, Resources. **Bo Du**: Conceptualization, Writing - review & editing, Supervision.

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