

A Technical and Financial Analysis of Potentially Near-Zero Greenhouse Gas Emission Passenger Vehicles

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ABSTRACT

This paper presents a technical and financial analysis of several, potentially near-zero greenhouse gas emission passenger vehicles for Australian driving conditions. Conventional, series hybrid, plug-in hybrid (PHEV) and fully electric (BEV) vehicles of class B and class E sizes are considered, with their propulsive energy assumed to originate from a source that is free of net greenhouse gas emissions.

Extensions to the vehicle models developed by the authors in our previous works [1, 2, 3] are first developed. These enable estimation of the size of each major component in each powertrain, and therefore the total, in-service energy consumption and in-service greenhouse gas emissions. The component sizing also allows estimation of the each vehicle's purchase price, its embodied energy and its embodied greenhouse gas emissions, the latter assuming scenarios for both the current and a future, low emission intensity of Australian manufacturing.

The ability of increasingly electric powertrains to reduce in-service energy consumption and emissions, with correspondingly higher up-front price and higher embodied emissions, are then evaluated. Overall, the results suggest that full vehicle electrification is not the clear end-point in the evolution of the passenger vehicle powertrain, since PHEVs/BEVs may perform worse environmentally, financially and in utility than alternatives. A technologically neutral approach to the progressive reduction of passenger vehicle lifecycle emissions therefore appears appropriate, with the hydrogen economy one potential outcome and the continued use of the internal combustion engine appearing likely. Such an approach is thought to minimise the risk of perverse incentives, both today and in future, as this paper suggests could occur if fully electric vehicles are given preferential treatment.

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INTRODUCTION

The debate on which passenger vehicle technologies are best placed to help meet environmental, economic or social goals is always active and often contested. The numerous different technologies available each have their proponents and critics, e.g. [4, 5, 6, 7, 8, 9, 10, 11, 12]: biofuels, fuel synthesis with and without carbon capture and storage (CCS), electric vehicles, fuel cells, hybrids, the 'hydrogen economy' and the 'methanol economy', to name only a few.

There appears to be less general support today for the hydrogen economy than say 5-10 years ago. Its substantial technical challenges, particularly those of hydrogen generation, distribution and storage, have been discussed by many, e.g. [4,5,9]. Nonetheless, a common feature in much of

this discussion of a future hydrogen economy has been the assumption that fuel cell vehicles will be the dominant vehicle type. This is a surprising assumption, particularly since fuel cells are currently much more expensive and less robust than the internal combustion engine. Hydrogen fuelled, internal combustion engines are long established and can have superior efficiency and lower regulated pollutant emissions, but similar cost, to gasoline engines, e.g. [12, 13, 14]. Thus, it seems more plausible to the authors that the internal combustion engine will be the dominant *initial* form of power plant if the hydrogen economy is ever realized, with fuel cells taking market share if and when their cost becomes more competitive.

More recently, there has also been considerable interest in battery electric vehicles (BEVs). However, uptake of these vehicles has been relatively slow, with their high purchase price, limited range and recharging times often cited as issues. Recent analyses by ourselves and others have also called into question the lifecycle performance of BEVs even when their electricity comes from low greenhouse sources, with the embodied energy and emissions in their larger batteries being a significant contributor to their lifecycle performance [1, 2, 3, 15]. Further, our recent works [1, 2, 3] also show that both hybridisation of larger vehicles and vehicle downsizing are significantly more cost effective means of emissions mitigation than BEVs. Nonetheless, BEVs still provide a potential means of achieving near-zero greenhouse gas emission transportation since they make no direct, in-service use of fossil fuels.

In light of these recent analyses, we do not consider it obvious that BEVs are the ultimate end-point in the development of the passenger vehicle powertrain. This view is in part motivated by electricity not being the sole form of propulsive energy with potentially near-zero greenhouse gas emissions in-service. Hydrogen is one alternative, as are several other biologically-derived or synthesized liquid or gaseous fuels that make significant use of either renewable or nuclear energies, e.g. 'bio-' or synthetic natural gas, ethanol, methanol and gasoline/diesel [5, 6, 7, 8, 10, 11, 12, 13, 14]. Like electricity and BEVs, all of these alternatives have significant challenges, particularly in terms of cost, scalability and uncertainty in their environmental performance. However, unlike BEVs, these fuels can be used in either today's production vehicles and their fuel supply chain without modification, or require significantly less modification to either the vehicle or fuel supply chain to do so, and thus may be more plausible pathways to a lower greenhouse transport system.

This paper is therefore intended to be a transparent comparison between BEVs and perhaps the most challenging of these alternatives - hydrogen fuelled vehicles. It presents a technical and financial analysis of several, potentially near-zero greenhouse gas emission passenger vehicles for Australian driving conditions. For all vehicles that feature an internal combustion engine, either compressed hydrogen gas or conventional gasoline/diesel is the energy carrier. In all cases, the hydrogen and electricity is assumed to originate from a source that is free of greenhouse gas emissions.

It is emphasised that these results are *not* an endorsement of the hydrogen economy, whose substantial challenges must always be acknowledged. Rather, the results suggest that full vehicle electrification is not the clear end-point in the evolution of the passenger vehicle powertrain, since PHEVs/BEVs may perform worse environmentally, financially and in utility than alternatives. This is argued to be significant when considering transport policy, both today and in the future, and suggests that the continued use of the internal combustion engine appears likely, even if the 'fuel of the future' is less certain.

MODELLING

Vehicles of size classes E and B are considered. The class E vehicles use a recent model Ford Falcon as their reference, which is a larger passenger vehicle sedan with a 4lt, naturally aspirated, PFI gasoline engine and a 6 speed automatic transmission. The class B vehicles use as their reference the 1.6 litre TDCi 2010 Fiesta ECONetic. Details of the development of the models for these conventional vehicles are presented in our earlier works [1, 2, 3]. When the Powertrain System Analysis Toolkit (PSAT) from Argonne National Laboratories is run on these conventional vehicles, the calculated fuel consumption over the New European Drive Cycle (NEDC) is within 5% of that reported by the manufacturer, suggesting that our modeling is reasonable.

Since it is widely known that measured vehicle fuel consumption on the NEDC cycle significantly under-reports real-world fuel consumption, this paper instead uses the Australian Urban Drive Cycle (AUDC) shown in [Figure 1](#). The AUDC features stronger accelerations and decelerations than the NEDC, and results in higher fuel consumption that more closely approximates real-world conditions.

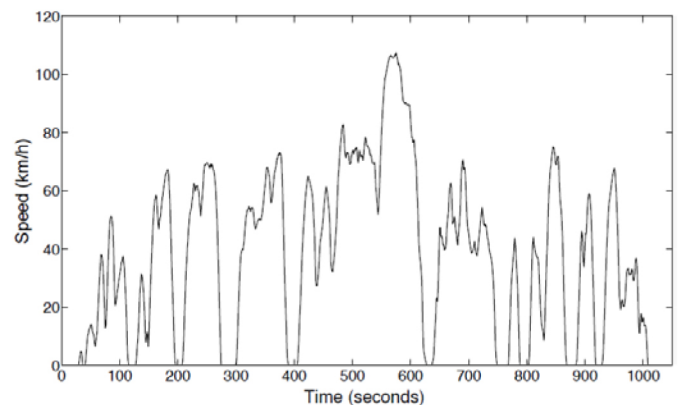


Figure 1. The Australian Urban Drive Cycle (AUDC)

Powertrain Modeling

The following variants of these class E and class B conventional vehicles (CV) are considered. The technical assumptions for each of these vehicles are stated in [Table 1](#) and used as inputs into PSAT. The models for the gasoline fuelled series hybrid and plug-in hybrids were developed in our prior works [1, 2, 3], and so are not discussed in detail in this paper.

1. Gasoline (E) or diesel (B) series hybrid (series)
2. Gasoline (E) or diesel (B) plug-in hybrid (plug-in)
3. Battery electric vehicle (BEV)
4. Hydrogen fuelled conventional vehicle (H₂ CV)
5. Hydrogen bi-fuelled conventional vehicle (H₂ bi-fuel)

6. Hydrogen fuelled series hybrid (H₂ series)

The resulting sizes of the major powertrain components (the engine, the battery and/or the generator, if applicable) are summarized in [Table 2](#) for each variant, as is the vehicle mass. The corresponding in-service energy consumption (hydrocarbon, hydrogen and/or electricity, if applicable) and ownership duration are listed in [Tables 3](#) and [4](#).

Table 1. Technical assumptions made for each vehicle

General	Lifetime distance travelled = 150,000km Base battery price = \$800 /kWhr capac. Base hydrocarbon fuel price = \$1.40 /lt Base hydrogen price = \$6 /kg Base electricity price = \$0.25 / kWhr All vehicles match CV driveability Li-ion batteries in all non-CVs
Gasoline/ diesel series	Controller strategy = on/off Minimum SOC = 60% Minimum SOC in hybrid mode = 70%
Gasoline/ diesel plug-in	All electric range = 60km Controller strategy = on/off Minimum SOC in electric mode = 25% Maximum SOC in hybrid mode = 30%
BEV	Minimum SOC = 20% Range = 160km
Hydrogen CV	Class E ICE +10% efficient than gasoline Class B ICE -10% efficient than diesel 700 bar gaseous hydrogen storage Hydrogen storage = 5% of storage weight Range = 160km
Hydrogen bi-fuel	Engine efficiency as for H ₂ CV 700 bar gaseous hydrogen storage Hydrogen storage = 5% of storage weight 160km range on hydrogen
Hydrogen series	Engine efficiency as for H ₂ CV Controller strategy = on/off Minimum SOC = 60% Maximum SOC in hybrid mode = 70% 700 bar gaseous hydrogen storage Hydrogen storage = 5% of storage weight

Conventional and bi-fuel hydrogen vehicles

It is reasonably commonly known that hydrogen fuelled spark ignition engines can have a significantly higher brake thermal efficiency than an equivalent gasoline fuelled engine, e.g. [12]. This is due to several factors, in particular hydrogen's ability to run very lean, as well as hydrogen's relatively high octane rating. As such, the class E hydrogen

fuelled CV vehicle is assumed to be 10% more efficient (relative) than its gasoline equivalent. The class B hydrogen fuelled CV is assumed to be 10% less efficient (relative) than the diesel equivalent, which is considered a more reasonable assumption given the modern diesel engine in this vehicle. The mass fraction of the hydrogen in the total storage system is assumed to be 5%, which is in keeping with recent reviews on high pressure, gaseous storage [16].

The hydrogen bi-fuel vehicles are modeled in a similar manner, with the hydrogen fuelled range specified in [Table 1](#). These vehicles would feature two sets of fuel injectors per cylinder - one for the gasoline/diesel injection and the other for the hydrogen - as well as two fuel tanks, and accommodation of the fuel switching in the powertrain controller. Given that bi-fuel vehicles are already widespread, particularly for gasoline/natural gas and gasoline/LPG, this is not a significant technical challenge.

These bi-fuelled vehicles are included as a purely combustion driven analogue to the plug-in hybrids. In both cases the vehicles can operate with nominally zero tailpipe emissions until the storage of the low emission energy carrier has reached a level where the fossil fuel needs to be used.

Battery electric and hybrid vehicles

The models for the class E and class B BEVs were developed in our prior works [1, 2, 3], with minor changes in some model inputs. The requirements in developing the BEV models require determination of the battery size and the electric motor to meet range and drivability requirements respectively. The electric motor size is governed by the driveability requirements of the reference CVs, resulting in 145kW/400Nm and 75kW/240Nm motors for the Class E and Class B vehicles respectively. The resulting battery capacities for the two vehicle classes are 33kWh and 17 kWh respectively.

The plug-in and series hybrid models have essentially the same powertrain configuration. As with the hydrogen fuelled CVs, the engine for the class E hydrogen fuelled series hybrid was assumed to be 10% more efficient than its gasoline equivalent, whilst that of the class B hydrogen fuelled series hybrid was assumed to be 10% less efficient than its diesel equivalent. Both the plug-in and series hybrids feature an electric motor that propels the vehicle and the engine as an electrical generator. Since the electric motor provides the propulsion, the drivability constraint requires that the electric motor for both the plug-in and series vehicles must be the same size as the equivalent BEV. For the plug-in hybrid, the engine operates in so-called 'switching mode', i.e. the vehicle operates in a charge depletion mode until the battery's state of charge (SOC) meets a specified minimum limit. Once this limit is reached, the vehicle enters and remains in a charge sustaining mode, where the engine driven generator remains at maximum efficiency until an upper SOC limit is reached, at which point the engine switches off again. The series hybrid then uses the same battery control approach, but

without the initial 'all electric range (AER)' and corresponding initial charge depletion strategy.

The optimal battery capacity N_B for the plug-in hybrid was estimated by minimizing the total cost J_B associated with a given battery capacity. This requires estimation of several terms in the following relationship.

$$J_B = P_B N_B + D \left[(1-u) P_{fuel} C_f (N_B) + u P_{elec} C_e (N_B) \right]. \quad (1)$$

The utility factor u represents the fraction of time spent in charge depletion mode according to the SAE J1711 standard, and is set to 0.79 as justified in our previous works [1,2]. The electricity consumption C_e in kWh/km during charge depletion mode is estimated by running PSAT for these vehicles over the AUDC drive cycle with an initial state of charge at 80%. The fuel consumption C_f in litres/km during the charge sustaining or hybrid simulation is repeated with an initial battery state of charge equal to the minimum limit. Both C_e and C_f are functions of the battery capacity N_B . The terms P_B , P_{fuel} and P_{elec} are the specific battery, fuel and electricity prices listed in Table 1.

Equation (1) is also used to calculate the optimum battery size for the series hybrid. However, in this case the utility factor $u=0$ as the vehicle does not have an all electric range. The resulting differences in the sizes of the plug-in and series battery packs is the result of the plug-in having a non-zero AER.

Component and vehicle masses

The software package 'Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET)' version 2.7 [17] is used to estimate the material and the mass of the vehicle components. The mass of each of these components is estimated using the component size estimates in Table 2. The vehicle components are classified into 6 groups.

1. The glider - The 'glider' is the vehicle without a powertrain. The glider mass estimates were assumed constant for each vehicle class, and were determined by subtracting the engine and transmission masses from the total mass of the CVs.

2. The powertrain

3. The transmission

4. The motor/generator

5. The batteries

6. Fuel / fuel systems - The hydrogen storage systems is assumed to have 5% by mass hydrogen, i.e. almost all of the mass is the storage system rather than the fuel, in keeping with the literature [16]. The hydrocarbon storage mass is the mass of the fuel only.

The estimated mass of each component group is presented in Table 5. It is noted that the mass of the driver/wheels are

shown in Table 5 as separate to the glider, but is included with the glider in later analyses.

Table 2. Summary of key vehicle parameters from the PSAT modeling

	Vehicle	Engine	Electric Motor (kW / Nm)	Battery Size (kWh)	Vehicle Mass (kg)
Class E	CV	I6, 4 Litre, 195 kW	-	Pb	1910
	Series	I4, 1.6 Litre, 85 kW	145 / 400	2.6	1867
	PHEV	I4, 1.6 Litre, 85 kW	145 / 400	13.1	2071
	BEV	-	145 / 400	32.9	2182
	H2 CV	I6, 4 Litre, 195 kW	-	Pb	1964
	H2 Bi-Fuel	I6, 4 Litre, 195 kW	-	Pb	2030
	H2 Series	I4, 1.6 Litre, 85 kW	145 / 400	2.6	1942
Class B	CV	I4, 1.6 Litre, 66kW	-	Pb	1097
	Series	I4, 1.6 Litre, 66kW	75 / 240	2.2	1185
	PHEV	I4, 1.6 Litre, 66kW	75 / 240	7.6	1289
	BEV	-	75 / 240	16.8	1197
	H2 CV	I4, 1.6 Litre, 66kW	-	Pb	1112
	H2 Bi-Fuel	I4, 1.6 Litre, 66kW	-	Pb	1162
	H2 Series	I4, 1.6 Litre, 66kW	75 / 240	2.2	1200

Table 3. Hydrocarbon, hydrogen and electricity in-service consumption of the modeled vehicles

	Vehicle	HC Fuel L/100km	H2 kg/100km	Electricity kWh/km
Class E	CV	11.8	-	-
	Series	6.7	-	-
	PHEV	1.3	-	0.135
	BEV	-	-	0.172
	H2 CV	-	2.87	-
	H2 Bi-Fuel	0	2.93	-
	H2 Series	-	1.65	-
Class B	CV	4.5	-	-
	Series	2.6	-	-
	PHEV	0.58	-	0.077
	BEV	-	-	0.090
	H2 CV	-	1.47	-
	H2 Bi-Fuel	0	1.51	-
	H2 Series	-	0.90	-

Table 4. Additional assumptions used in estimating the in-service vehicle emissions and cost of ownership

Vehicle ownership, years	10
Discount rate, %	6
Transmission cost, \$	$12.5(kW_{eng} + kW_{motor})$
Motor/generator cost, \$	$425 + 21.7kW_{motor}$
Engine cost, \$	$531 + 13.5kW_{motor}$
Retail markup	1.713
Class E on-road costs, \$	4304
Class B on-road costs, \$	3313

Table 5. Estimated component masses (kg) for the Class E and Class B vehicles

	Class-E						
	CV	Series	PHEV	Electric	H2 CV	H2 Bi-Fuel	H2 Series
Glider	1258	1258	1258	1258	1258	1258	1258
Powertrain	265	167	167	15	265	265	167
Transmission	107	40	40	30	107	107	40
Motor/Generator	7	126	126	66	7	7	126
Batteries	28	51	255	638	28	28	51
Fuel/Fuel Systems	71	50	50	0	125	191	125
Driver/Wheels	175	175	175	175	175	175	175
Total	1910	1867	2071	2182	1964	2030	1942

	Class-B						
	CV	Series	PHEV	Electric	H2 CV	H2 Bi-Fuel	H2 Series
Glider	640	640	640	640	640	640	640
Powertrain	193	181	181	11	193	193	181
Transmission	56	27	27	21	56	56	27
Motor/Generator	4	105	105	57	4	4	105
Batteries	15	43	147	333	15	15	43
Fuel/Fuel Systems	55	55	55	0	70	120	70
Driver/Wheels	135	135	135	135	135	135	135
Total	1097	1185	1289	1197	1112	1162	1200

Lifecycle Emissions Modeling

The lifecycle CO_2e emissions are calculated by adding together the embodied and the in-service emissions of each Class E and Class B variant. Each vehicle's embodied emissions are estimated by first estimating their embodied energy, and then using representative emission intensities t_{CO_2e}/GJ to calculate the associated embodied emissions [3]. The in-service emissions are determined by using the fuel and electricity consumption estimates obtained earlier (Table 3), assumptions on the vehicle distance travelled (Table 1) and ownership duration (Table 4), as well as estimates of the emissions associated with in-service replacements and the indirect emissions from each energy source.

The emissions associated with vehicle disposal have been excluded. This is not expected to result in significant errors since these emissions are small. Further, there is significant uncertainty in systematically estimating these emissions for the hybrid and battery electric vehicles.

Embodied energy and emissions

The embodied energy and emissions are assumed to consist only of those arising from the materials used, as well as those due to vehicle assembly. The material emissions are estimated using the mass estimates in Table 5, as well as GREET's estimated percentages of the different materials in each major component group. For each of these major component groups, the energy coefficient GJ/kg corresponding to Australian manufacturing of each of these materials [3] is multiplied by the mass of the respective

material in that component group, and results in a total embodied energy per major component. The embodied emissions are then obtained from the embodied energy using an emissions intensity. In the case of current manufacturing, this intensity is $60 \text{ kgCO}_2e/GJ$, and is based on the current Australian fuel mix, which is primarily coal with some gas, oil and renewables [3].

The energy required for vehicle assembly is not available in the public domain. It is therefore estimated using an energy based input-output model for Australia [3] and the estimated vehicle component costs (Table 6, discussed in detail later in this paper). The energy required for vehicle assembly is assumed to be 0.3603 GJ per $\$1000$ of the vehicle retail price [3]. Although this approach should be a good approximation across manufacturing sectors, its use will yield some error as the retail price of each vehicle is not a sole function of the energy spent in the vehicle assembly. However, the emissions due to the vehicle assembly are a relatively small part of the total lifecycle emissions [18], and so more sophisticated approaches are not justified for the present study.

In-service energy and emissions

The in-service energy and emissions are classed in three groups: direct, indirect and replacement. Direct emissions are those emitted from the tailpipe during vehicle service. The indirect emissions are associated with the production of the propulsive energy, i.e. that due to gasoline, diesel, hydrogen or electricity production and distribution. The replacement emissions are those attributed to the periodic replacement of consumables. Our previous works [1, 2, 3] found that these

replacement emissions are much smaller than the other two forms of in-service emissions.

The direct, in-service energy and emissions are calculated from the drive cycle fuel consumption (Table 3), the annual range (Table 1) and the ownership duration (Table 4). The hydrogen fuelled variants have zero direct emissions since the product of hydrogen combustion is water. The direct, in-service energy for the hydrogen vehicles is that required to produce the hydrogen from the electrolysis of water at an efficiency of 60%. This is a reasonable efficiency for a modern, high pressure electrolyser [19], and enables a fairer comparison between the energy propelling the BEVs, PHEVs and hydrogen vehicles. Of course, the hydrogen may not be produced from electricity in practice, emphasizing that care is required when comparing the in-service energy of all vehicles.

The indirect, in-service energy and emissions depend on the particular energy carrier for a given vehicle. If this energy carrier is gasoline or diesel, these emissions include the extraction, production and transportation of the fuel, and are detailed in our companion works [1, 2, 3]. If this energy is electricity or hydrogen, we have assumed in this study that the indirect emissions are zero.

Embodied, in-service and lifecycle energy and emissions

Given these means of estimating the embodied and in-service energy and emissions, we are now in a position to examine the lifecycle emissions of each class E and class B variant. The embodied energy and emissions are first noted (Figure 2). The results for the CVs are comparable to, but higher than those of some other studies [10, 18]. This is thought to be due to both the material energy coefficients of Australian manufacturing and the current Australian emissions intensity. As discussed in detail in our previous work [3], there is a significant rise in the embodied emissions for each hydrocarbon fuelled class E and class B vehicle as its becomes more electrified, i.e. starting from each respective CV, progressing through the series, PHEV and BEV equivalents. This rise in embodied emissions is almost entirely due to the battery. Indeed, the BEV variants in both class E and class B have the highest embodied emissions of any of the vehicles considered.

It is this embodied emissions penalty due to electrification that the hydrogen fuelled variants exploit. Figure 2 shows that each hydrogen fuelled vehicle has similar embodied emissions to their equivalent CV. This similarity is not surprising; these vehicles have either roughly the same configuration as a CV or, in the case of the series hybrid, a small battery size that avoids a large embodied emissions penalty.

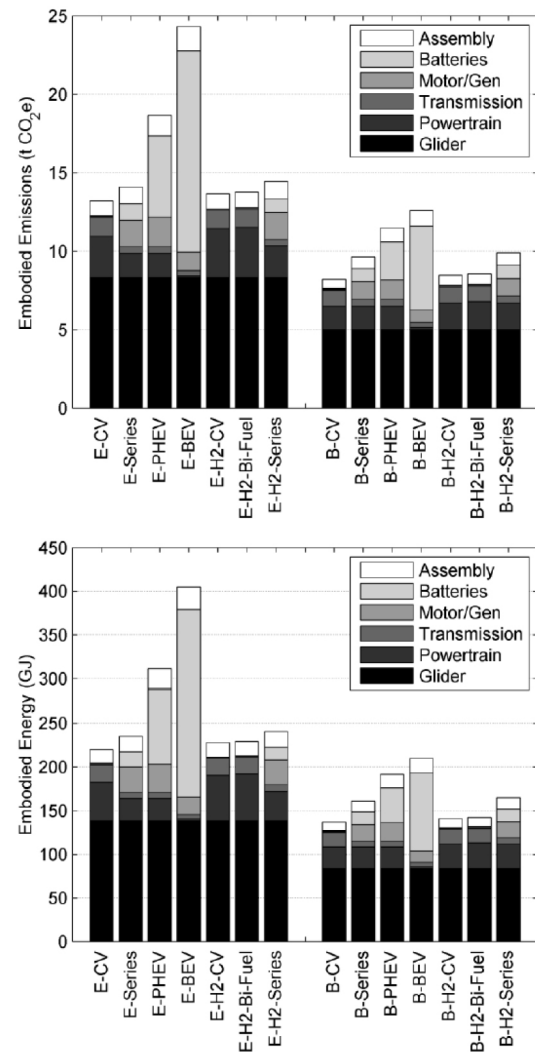


Figure 2. Embodied energy and emissions of each vehicle assuming current energy mix

Figure 3 shows that the BEV and all hydrogen fuelled variants have similar, very low, in-service emissions because we have assumed that both the electricity and the hydrogen have zero in-service direct and indirect emissions. These in-service emissions are significantly lower than the hydrocarbon fuelled CV, series hybrid and PHEV variants also shown. Of note, however, is the high in-service energy consumption of the hydrogen fuelled vehicles. This is due to both the energy losses in electrolysis and combustion. Importantly, hybridization offsets this energy consumption significantly, such that these vehicles have comparable, in-service energy consumption to the equivalent, fossil fuelled CVs.

Because these in-service emissions for the BEV and hydrogen fuelled variants are all so low, the lifecycle emissions of these vehicles are essentially their embodied emissions (Figure 4). As a result, relative to the hydrogen fuelled variants, it is not possible for the BEVs to compensate for their high embodied emissions through low in-service