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Techno-economic comparison of series hybrid, plug-in hybrid, fuel cell and regular cars

Oscar P.R. van Vliet*, Thomas Kruithof, Wim C. Turkenburg, André P.C. Faaij

Utrecht University, Copernicus Institute, Science, Technology and Society Group, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

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ABSTRACT

We examine the competitiveness of series hybrid compared to fuel cell, parallel hybrid, and regular cars. We use public domain data to determine efficiency, fuel consumption, total costs of ownership and greenhouse gas emissions resulting from drivetrain choices. The series hybrid drivetrain can be seen both as an alternative to petrol, diesel and parallel hybrid cars, as well as an intermediate stage towards fully electric or fuel cell cars.

We calculate the fuel consumption and costs of four diesel-fuelled series hybrid, four plug-in hybrid and four fuel cell car configurations, and compared these to three reference cars. We find that series hybrid cars may reduce fuel consumption by 34–47%, but cost €5000–12,000 more. Well-to-wheel greenhouse gas emissions may be reduced to 89–103 g CO_2 km^{-1} compared to reference petrol (163 g km^{-1}) and diesel cars (156 g km^{-1}). Series hybrid cars with wheel motors have lower weight and 7–21% lower fuel consumption than those with central electric motors.

The fuel cell car remains uncompetitive even if production costs of fuel cells come down by 90%. Plug-in hybrid cars are competitive when driving large distances on electricity, and/or if cost of batteries come down substantially. Well-to-wheel greenhouse gas emissions may be reduced to 60–69 g CO_2 km^{-1}.

1. Introduction

More than 90% of the transport sector is powered by fuels derived from oil. However, the consumption of these fuels is considered problematic due to costs of oil, doubts about of security of supplies [1,2], greenhouse gas (GHG) emissions, and the emissions of air pollutants such as NO_x, PM_{10} and volatile organic compounds [3,4].

To reduce dependence on oil in transport, the use of hydrogen and electricity in cars has been advocated for decades [5–7]. Hydrogen can be converted to electricity in a fuel cell (FC) car with high efficiency, generating no tailpipe CO_2 emissions and hardly any other pollutants [8]. However, a costly infrastructure to distribute and store hydrogen will be required [9,10]. Hydrogen and electricity can be produced from a wide variety of energy sources; fossil, nuclear as well as renewable. Both can therefore decrease the dependence on fossil energy sources and increase energy security [11,12]. However, costs of fuel cells and batteries remain high. Researchers give varied and uncertain appraisals of the development of the costs of alternative drivetrains [13–17].

Recent developments show that hybrid cars such as the Toyota Prius and Honda Civic hybrid have lower fuel consumption and thereby lower emissions than cars driven by internal combustion engines (ICEs) only. Although the Prius is more expensive than a comparable ICE car, over 1 million units have been sold as of 2007 [18], showing that there is a market for alternative drivetrains. As of 2008, hybrid cars have received more and more attention. With many manufacturers selling or preparing new models, hybrid cars seem to be on the verge of mainstream adoption.

Research by Demirdöven and Deutch [19] and the EU JRC [20] has shown that the performance of current FC drivetrains is comparable to the performance of a parallel hybrid drivetrain. However, the FC drive train has more potential for reducing emissions on the long term.

In these studies, the series hybrid drivetrain was not taken into account. In this drivetrain, the ICE is only used to generate electricity and not to power the wheels directly: only an electric motor drives the wheels. The series hybrid drivetrain can be seen both as an alternative to regular cars and parallel hybrids, as well as an intermediate stage towards fully electric or fuel cell cars: It avoids both the limited range and recharging issues of an electric car, as well as the expensive fuel cells and the lack of infrastructure for refuelling a hydrogen car. The Chevrolet Volt was announced as the first series hybrid in mass production, and is to go on sale in 2010 [21].

In this article, we examine the competitiveness of series hybrid compared to fuel cell, parallel hybrid, and regular cars. We use public domain data to determine efficiency, fuel consumption, total

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* Corresponding author. Tel.: +31 030 253 7646; fax: +31 030 253 7601.
E-mail address: o.p.r.vanvliet@uu.nl (O.P.R. van Vliet).

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costs of ownership (TCO) and GHG emissions resulting from drivetrain choices. We investigate if series hybrid technology can make cars more efficient, particularly in view of the possibility in a series drivetrain to replace the central electric motor and transmission with electric motors built into the wheels.

Production costs of ICEs are widely available in the public domain [20,22]. This is not the case for alternative drivetrains, but much research was performed on single components using technological learning, analogy studies and manufacturer overviews to estimate future costs [23–25]. Production costs of a series hybrid drivetrain are expected to be higher than for an ICE drivetrain, because series hybrid drivetrains have larger electric motors and components that are not yet mass produced.

Operating costs of ICE drivetrains are known in detail [26,27,20], but there are little data available in the public domain on costs of operating alternative drivetrains and their influence on the total cost of ownership of a car.

We therefore aim to answer the following three questions in this article:

- What are the costs and fuel consumption of electric drivetrains, powered by fuel cells or as a series hybrid?
- What are the TCO and well-to-wheel GHG emissions of using a fuel cell or series hybrid car, in the short and medium term?
- Depending on driving habits, which among the ICE, FC, and hybrid cars would attain the lowest total cost of driving?

We describe our research methods in Section 2, and derive costs and fuel consumption for components in Section 3. We define 15 vehicle configurations, and derive their costs and well-to-wheel emissions in Section 4. We derive TCO, also depending on driving habits in Section 5. Finally, we discuss our results and uncertainties in Section 6. Conclusions are drawn in Section 7.

2. Methods

2.1. Drivetrains

The drivetrain consists of parts that contribute to the conversion of fuel in the tank into kinetic energy in the wheels. Fig. 1 shows a diagram of different drivetrains.

Reference diesel drivetrain

The reference car is a compact 5-seater, the most widely used car class in NL that includes the VW Golf, Ford Focus, Renault Megane, Toyota Corolla and Opel Astra [20,28]. We use a reference drivetrain with properties similar to the diesel Golf drivetrain (see Fig. 1a).

Hybrid drivetrain

Parallel hybrid cars, such as the Civic hybrid, have an ICE and a small electric motor. The electric motor and the ICE can both deliver power to the wheels (see Fig. 1b). Fuel consumption is slightly lower than for regular ICE cars [19,20]. Series hybrid cars use an engine-generator and a separate electric motor to power the wheels (see Fig. 1c). Mixing these designs is also possible, as done in the Prius.

The electric motor in a series hybrid car can be installed as a central motor, using a gearbox and differential like a regular car, like in the Volt. Alternatively, electric motors can be installed in the hubs of the wheels of the car, like in the Volvo C30 Recharge and Hi-Pa Drive Ford F150 concept cars and e-Traction busses and trucks. The latter drivetrain does not require the use of a gearbox because the larger diameter allows wheel motors to deliver sufficient torque (see Fig. 1e).

Fuel cell drivetrain

The FC drive train is very similar to the series hybrid drive train, but it replaces the engine-generator and conventional fuel tank with a fuel cell and hydrogen storage device (see Fig. 1d and f). We do not consider fuel cells with a fuel reformer because of the extra cost and reduction in energy efficiency introduced by a reformer (cf. [20]).

2.1.1. Reference car

Our reference car has a 74 kW diesel-fuelled direct injection ICE. Main characteristics of the reference car are shown in Table 1.

The vehicle platform is defined as everything but the drivetrain, such as chassis, suspension, doors, seats, windows, and assembly. Like Weiss et al. and the EU Joint Research Centre (JRC) [26,20], we use the same platform for our hybrid and fuel cell configurations, exchanging only the drivetrain. The fuel consumption of the reference car is based on the New European Driving Cycle (NEDC) driving cycle.

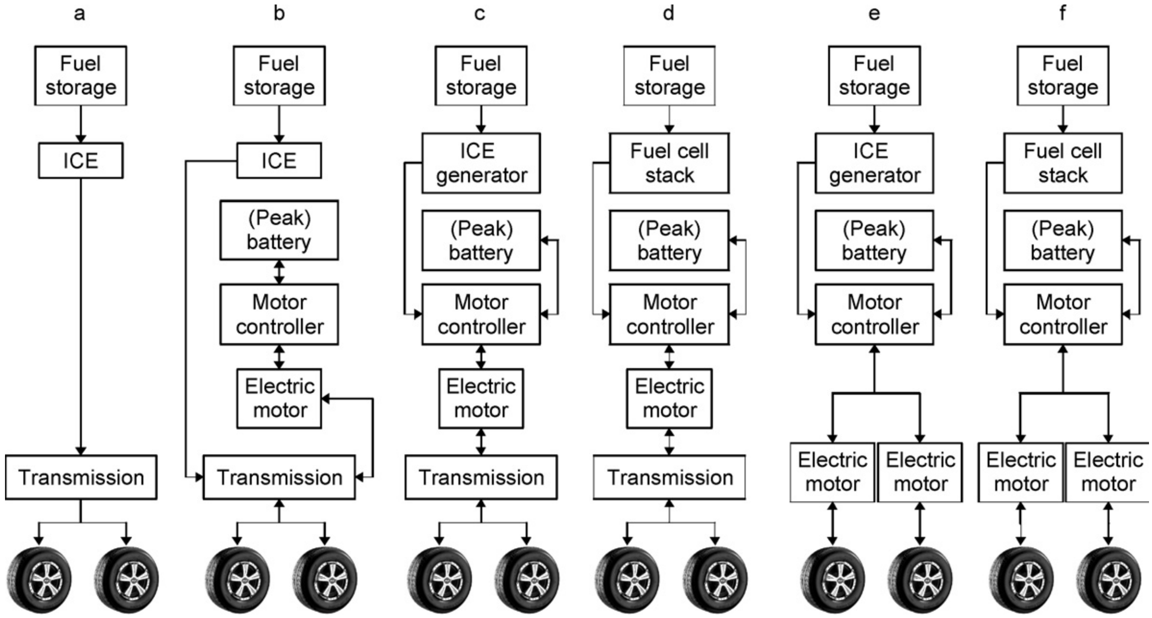

Fig. 1. Diagram of the energy flows in six different types of drives trains; ICE drivetrain (a); parallel hybrid drivetrain (b); series hybrid drivetrain with central motor (c); fuel cell drivetrain with central motor (d); series hybrid drivetrain with wheel motors (e) and fuel cell drivetrain with wheel motors (f).

Table 1
Characteristics of the diesel ICE reference car [29, 2010 DICI in 20].

Vehicle characteristics		Components	Weight (kg)	Cost (€)
Engine power (kW)	74	Vehicle platform	1016	15,725
Auxiliaries power use (kW)	0.3	Diesel engine	145	4080
Torque (N m in 1st gear, approximately)	520	Basic starter and alternator	0	300
Coefficient of rolling resistance	0.01	Gearbox	50	n/a[a]
Coefficient of drag	0.32	3-Way catalyst	0	430
Surface area (m^2)	2.10	Euro IV after-treatment	0	300
Fuel consumption (MJ km^{-1})	1.77	Diesel particulate filter	0	400
Approximate range (km)	550	Fuel tank	15	125
Maintenance cost (€ km^{-1})	0.043	Diesel 90% full tank	23	
		Totals	1248	21,360

[a] Gearbox cost is included in engine cost.

For the TCO comparison, we also use the petrol equivalent of the reference car and a parallel hybrid car. The petrol reference car has a petrol consumption of 1.90 MJ km^{-1} and costs €19,160 to purchase. We use a parallel hybrid configuration from JRC which has a petrol consumption of 1.51 MJ km^{-1} with a battery that allows for 20 km of electric driving [20], and that we recalculated to cost €24,950.

2.1.2. *Future developments in the reference drivetrain*

Several assessments have been made of future developments of ICE efficiency. Estimates of efficiency increases until 2020 range between 7.5% [30] and 25% [31]. These fuel consumption benefits are reached through downsizing of the engine, better variable valve timing and a more efficient gearbox. Others claim that more stringent emission laws will compensate possible efficiency improvements and therefore do not expect large efficiency improvements for the ICE [20].

Improvements in baseline ICE carry over into parallel and series hybrid cars (which also use ICE), and fuel cells are also likely to improve. Because unknown but similar efficiency improvements do not essentially change the comparison between different drivetrains, we use current efficiency data for all drivetrain components.

We expect that the production costs of an ICE drivetrain of 74 kW will stay around €2600 for a petrol engine and €4300 for a diesel engine [20].

2.2. *Drivetrain efficiency*

To derive the efficiency of a series hybrid drivetrain, we use the electricity consumption of electric cars, because the motor and transmission are the same. Total energy required for driving an electric car at a constant speed can be calculated as follows:

$$P_{\text{total}} = \frac{(P_{\text{tire friction}} + P_{\text{drag}})/\eta_{\text{transmission}}}{\eta_{\text{motor}}} + P_{\text{auxillaries}}$$

$$P_{\text{tire friction}} = C_{\text{rr}} \times m \times g \times v$$

$$P_{\text{drag}} = \tfrac{1}{2}\rho \times v^3 \times A \times C_{\text{d}}$$

in which η_{motor} is the efficiency of the electric motor, $\eta_{\text{transmission}}$ the efficiency of the transmission (axles, gearbox, differential, etc.), $P_{\text{tire friction}}$ the power needed to overcome rolling resistance, P_{drag} the power needed to overcome drag, C_{rr} the rolling resistance coefficient, m the mass of the vehicle (kg), g the gravitational acceleration constant (9.81 m s^{-2}), v the velocity of the vehicle (m s^{-1}), ρ the density of air (1.22 kg m^{-3}), A the frontal area of the vehicle (m^2), C_{d} the coefficient of drag, and $P_{\text{auxiliaries}}$ is the power needed run auxiliaries (air condition, car stereo, etc.). We define the transmission efficiency as the mechanical power exerted by the wheels divided by the mechanical power generated by the motor. For a wheel motor, by definition, $\eta_{\text{transmission}} = 1$.

The prime advantage of hybrid cars is that much of the energy that is lost in braking in a regular car can be recovered and used for acceleration, also depending on the efficiency of the battery.

In a series hybrid, the total efficiency is further influenced by the η_{ICE} and $\eta_{\text{generator}}$ ($\approx\eta_{\text{motor}}$). For a series hybrid to be more efficient than a parallel hybrid, the losses due to η_{motor} and $\eta_{\text{generator}}$ that result from the engine indirectly driving the wheels, must be smaller than the benefits from resizing and balancing the load on the ICE that are possible [32].

2.3. *Total cost of ownership*

We calculate the TCO in € $year^{-1}$ as a function of the fixed costs of the car, composed of a chassis and drivetrain, and the variable costs, composed of maintenance, repair and tires (MRT) and fuel costs.

We use analogies, expert opinions and data from the literature. In the case of technological analogy, the key factors determining the price of a product are identified and compared to similar technologies [33]. Because of a lack of data, we have been largely unable to use quantitative methods such as experience curves (as described in [24,34–36]).

2.3.1. *Fixed costs (initial purchase)*

Purchase cost of estimates of the drivetrains are based on costs and cost estimates of components from publically available literature sources. We use an annuity factor to convert the purchase cost to annual capital costs, with a commercial lifespan of 10 years [37].

For investment costs, harmonised EU-25 average consumer price indices from 1996 to 2007 [38] are used to compensate for inflation in data from years other than 2005. Costs in non-Euro currencies are converted to Euro first, using Interbank currency exchange rates averaged over the entire year [39], and corrected for inflation afterwards.

2.3.2. *Variable costs (lifetime, maintenance, repair and tires)*

The costs for maintenance, repair and tires (MRT) are expressed in € km^{-1} and are not constant. In general, an older drivetrain has higher maintenance and repair (M&R) costs than a new drivetrain. Drivetrain maintenance and repair is only a part of the total MRT cost. We use an average MRT cost of 4.3 €ct km^{-1} for the first 120,000 km for a compact European diesel car [29]. We assume that the MRT cost is the same for the remainder of the car's lifespan. Average MRT for the first 60,000 km is 3.8 €ct km^{-1} for a similar petrol car and for a petrol-fuelled hybrid [29]. We assume MRT of a petrol-fuelled car is equal to 4.3 €ct km^{-1} of the diesel car for the remainder of its lifespan.

The lifespan of an ICE drivetrain can be between 192,000 km [40] and 240,000 km [41]. We assume an average lifespan of drivetrains of 200,000 km, though the drivetrain must be designed to last far beyond this average. We therefore assume a design lifespan of 300,000 km.

The NEDC is supposed to reflect an average driving pattern, and the average velocity of a car in the NEDC is 34 km h^{-1} [42]. With an average drivetrain lifespan of 200,000 km, the drive train must function for at least 6000 h on average, and be designed to last up to 9000 h.

2.3.3. Fuel costs

We initially assume an oil price of 80 \$ bbl^{-1}, close to the short term projections in the World Energy Outlook 2009 [43]. At this oil price, assuming 41.87 MJ kg^{-1} and 820 kg m^{-3} for crude oil, fuel prices at the pump in the Netherlands are around 1.21 € l^{-1} for diesel and 1.40 € l^{-1} for petrol (using [44,45,20]). This includes 19% value-added tax (VAT) and excise duty (cf. [46]). Untaxed, prices are 19.3 € GJ_{LHV}^{-1} or 0.69 € l^{-1} for diesel and 19.9 € GJ_{LHV}^{-1} or 0.64 € l^{-1} for petrol.

Electricity from the grid is not taxed as a transport fuel, but it is subject to energy taxes in NL. The exact price of electricity from the grid depends on several factors, including quantity, time of use (separate tariffs for daily and nocturnal use), network operator and the provider. We use the average of variable home-use tariffs of grid electricity in NL in early 2009 of several large Dutch electricity suppliers (EON Benelux, Elektrabel, Eneco, Essent, Nuon, RWE Nederland). This grid price is 0.10 € kWh^{-1}, including VAT but excluding additional energy taxes (cf. [46]).

There is at present neither a large fleet of hydrogen powered cars nor a large network of hydrogen filling stations. However, the co-evolution of hydrogen-fuelled cars and the infrastructure for producing the hydrogen and refuelling the cars is beyond the scope of this article. Based on Shell data, Kramer et al. [47] have estimated the costs of production and distribution of hydrogen from coal at 4.5 € kg^{-1} as of 2020, excluding VAT. This is equivalent to a price of hydrogen of 44.3 € GJ_{LHV}^{-1} including VAT. We use this as baseline price for hydrogen produced on a large scale.

Fuel costs are summarised in Fig. 2.

2.4. Uncertainties

Available data are often not precise. Uncertainty in efficiency and TCO of our selected configurations is calculated as standard deviation (σ) from the indicated value. The costs of most drivetrains components depend on configurations but not on each other, and therefore have independent cost uncertainties. We therefore assume no co-variance for propagation of uncertainty in independent components and full co-variance if the cost uncertainties derive from the same underlying variable.

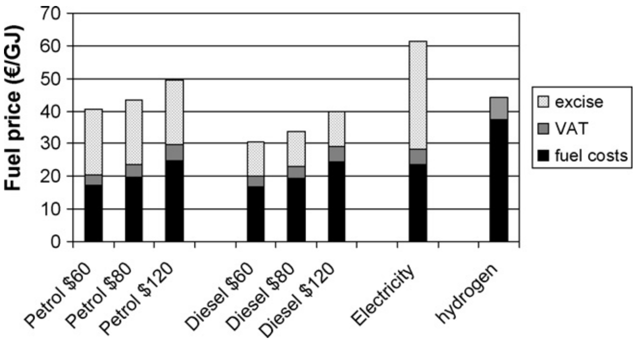

Fig. 2. Breakdown of fuel prices into fuel costs and taxes.

Table 3
Mass, surface area, C_d and C_{rr} for RAV4 EV and EV1 [48,52–54].

	Toyota RAV4 EV	GM EV1
Mass (kg)	1510	1347
A (m^2)	2.8	1.89
C_d	0.35	0.20
C_{rr}	0.0027 or 0.0045	0.005 or 0.008

In cases where either an upper or a lower bound exceeded a realistic value (for instance, upper bound of a future cost > known current costs), we assumed an uncertainty of $\sigma_x = |x'_{\text{unknown}} - x_{\text{certain}}|/2$. The same correction was applied to cases where $\sigma_x > x$ (which makes no sense for costs).

3. Hybrid drivetrain

3.1. Electric drivetrain efficiency

There are no series hybrid cars or fuel cell cars sold to consumers at this time. However, the drivetrain of a series hybrid car does not differ from a battery electric car (BEV). The only difference is that the series hybrid car has a generator to get a larger driving range and therefore the battery can be smaller.

Among electric cars used by consumers are the current Tesla Roadster, the late Toyota RAV4 EV and General Motors EV1. Plug-in conversions also exist of the Prius, by Hymotion and Energy CS, as do electrical versions of many other cars. These cars can be used to calculate the electricity consumption of a series hybrid car with a central electric motor.

The set of fuel consumption data in Table 2 yielded a simple average consumption of 103 ± 20 Wh km^{-1} for the whole vehicle on the SAE J1634 drive cycle. Variations are due to weight and shape of the cars, as well as the components used in the drivetrains.

To determine the losses in various components of the drivetrain (losses in the electric motor and transmission, air drag, tire friction, power for auxiliaries), we further examined the RAV4 EV and EV1. The resistance that the car has to overcome on a flat road is the sum of the rolling resistance and drag. The difference between the

Table 2
Electricity consumption (in drive cycle) of selected electric cars.

Electricity consumed (Wh km^{-1})	General EV1[a]	Motors mid-size[b]	Toyota RAV4 EV[a]	Energy CS Prius[a]	Hymotion Prius[a]	Tesla Roadster[c]
Aggregated only	96	145	131			110
Cold start						
No air conditioning				91	79	
With air conditioning				108	107	
Warm start						
No air conditioning				82	79	
With air conditioning				104	106	

We assume an AC to battery charging efficiency of 90% and a 96% battery discharge efficiency for the Prius models [51].

[a] *Source*: Idaho National Laboratory [48].

[b] *Source*: General Motors [49] (approximate mid-size vehicle simulation result).

[c] *Source*: Tesla Motors [50].

Table 4
Power consumption, tire friction, drag, total resistance and drivetrain efficiency of the Toyota RAV4 EV, General Motors EV1 at 72 and 96 km h^{-1}.

	Toyota RAV4 EV				General Motors EV1			
Velocity (m s^{-1})	20	20	27	27	20	20	27	27
Electricity consumption (Wh km^{-1})	293	293	440	440	177	177	234	234
C_{rr}	0.0027	0.0045	0.0027	0.0045	0.005	0.008	0.005	0.008
Rolling resistance (kW)	0.80	1.34	1.07	1.79	1.33	2.13	1.77	2.84
Air resistance (kW)	4.87	4.87	11.54	11.54	1.83	1.83	4.34	4.34
Total resistance (kW)	5.67	6.21	12.61	13.32	3.16	3.96	6.11	7.17
Power to drivetrain (kW)	7.9	7.9	16.1	16.1	4.7	4.7	8.4	8.4
Power from source (kW)	8.2	8.2	16.4	16.4	5.0	5.0	8.7	8.7
PCE + motor efficiency	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Transmission efficiency	0.80	0.88	0.87	0.92	0.75	0.94	0.80	0.94
Combined drivetrain efficiency	0.72	0.79	0.78	0.83	0.68	0.85	0.72	0.85

Table 5
Electric motor costs.

Type	Fixed (€)	Variable (€ kW$_e$$^{-1}$)	Fixed (kg)	Variable (kg kW$_e$$^{-1}$)
AC induction motor[a]	–	13.0	5	1
BPM motor >20k[a]	107	17.0	5	1
BPM motor >200k[a]	–	15.1	5	1
Generic electric motor[b]	–	8.0	–	0.7

[a] *Source*: Delucchi et al. [41].
[b] *Source*: JRC [20].

power that the motor delivers and the total resistance is the energy lost in the drivetrain.

Table 3 shows the mass, surface area and drag coefficient of the RAV4 EV and EV1. Both electric cars use low-friction tires, and we calculate for both value we found for C_{rr}. Furthermore, we use an efficiency of 90% for electric motor and power controller electronics module (PCE) at constant speed, a 96% battery discharge efficiency and a power consumption of 0.3 kW for auxiliaries [20,50,51].

From known electricity consumption at fixed speeds [48,50], we calculate the drivetrain efficiency at velocities of 72 and 96 km h^{-1} (20 and 27 m s^{-1}) for the RAV4 EV and EV1, as shown in Table 4. We find an $\eta_{\text{transmission}}$ of 0.86 ± 0.07, which is similar to the 0.89 found in simulations by JRC [20].

For charging and discharging the battery, we use a combined efficiency of 94% [20]. We assume that half of the electricity generated by the on-board generator or fuel cell is charged and discharged through the battery, and the other half is used directly by the electric motor. For plug-in hybrids, we use efficiencies of 90% for charging the battery from the grid and 96% for discharging the battery [51].

3.2. Central electric motor

Almost all existing electric cars use a single motor and a simplified transmission to connect to the wheels.

Efficiency and fuel consumption

The costs of the electricity in the reference car depend on how that electricity is generated. We calculated that the central motor drivetrain with a generator or fuel cell and a battery uses 106 ± 21 Wh km^{-1}, including charge/discharge losses. If powered by the grid, conversion losses increase this to 119 ± 23 Wh km^{-1}.

Table 6
Electric motor controller costs.

Type	Fixed (€)	Variable (€ kW$_e$$^{-1}$)
AC induction controller >20k[a]	1205	8.6
AC induction controller >200k[a]	376	9.2
BPM controller >20k[a]	964	5.8
BPM controller >200k[a]	316	8.3
Generic controller[b]	–	19.0

[a] *Source*: Delucchi et al. [41].
[b] *Source*: JRC [20].

Production costs

The central electric motor consists of three parts, the motor itself, the control electronics and a gearbox especially designed for electric motors. Deluchi et al. [41] provided equations to calculate the production costs of these three components and the development of the production costs when the production volume is increased to 20,000 and 200,000 units year^{-1}. As sales of hybrid cars exceeded 300,000 units year^{-1} in the US alone in 2007 and 2008 [55], we use the 20,000 units year^{-1} costs as an upper bound and the 200,000 units year^{-1} costs as a lower bound. JRC also gave cost estimates for these components.

Table 5 shows the unit production cost estimates for electric motors. For small production volumes the fixed costs have a significant contribution to total production costs of brushless permanent magnet (BPM) motors.

Table 7
Transmission costs.

Type	Fixed (€)	Variable (€ kW$_e$$^{-1}$)	Fixed (kg)	Variable (kg kW$_e$$^{-1}$)
Gearbox and differential >20k[a]	971	19.3	–	0.4
Gearbox and differential >200k[a]	565	11.3	–	0.4
Hybrid drive adaptations[b]	2630	–	30	–

[a] *Source*: Delucchi et al. [41].
[b] *Source*: JRC [20].

Table 8
Breakdown of the production costs and weight for an electric drivetrain with a 74 kW central electric motor.

	Cost (€)	Weight (kg)
74 kW electric motor	1000 ± 281	74 ± 12
Controller	1324 ± 355	–
Gearbox	2144 ± 652	30
Total	4467 ± 1288	104 ± 12

Table 6 shows the unit production cost estimates for electric motor controllers. Again, fixed costs play a bigger role when the production volume is small.

The gearbox for a series hybrid is simpler and lighter than a regular gearbox. A single-speed gearbox for a 200 kW_e motor in an electric sports car weighs only 45 kg [56]. Table 7 shows unit costs of less powerful transmissions.

Table 8 lists total production costs for a 74 kW_e central electric motor, calculated by adding the average of production costs of the three different components.

Lifetime, maintenance and repair

As electric motors have fewer moving parts and face less temperature stress than an ICE, we expect the lifespan to exceed 6000 h. While electric motors are simpler in construction than ICE, dealerships currently lack experience in maintaining them. The M&R estimations diverge from 15% higher to 50% lower than an ICE car [41]. To be conservative and for the sake of simplicity, we assume the MRT costs are the same as those of the reference diesel car.

3.3. *Wheel electric motor*

A wheel motor is an electric motor built inside a wheel. The design was first used in a Lohner-Porsche of 1902. In most permanent magnet motors, the housing of the electromotor remains stationary and the centre spins inside it. In a wheel motor this is reversed: The rotor of the electric motor is built inside the rim and the stator is placed in the hub of the wheel. The stator is fitted with electromagnets and the rotor with permanent magnets. The maximum torque that can be generated depends on the diameter of the rim. A wheel motor drivetrain is more efficient than an ICE or a central electric motor, because no losses occur in the gearbox and differential.

Our wheel motor has power output similar to an existing e-Traction design, TheWheel SM 450 [57]. The wheel motor delivers a maximum torque of 400 N m and is installed in pairs for a total of 800 N m. Maximum power output is 29 kW per wheel motor, for a total of 58 kW per pair.

Efficiency and fuel consumption

Because wheel motor cars do not need a gearbox, differential or other parts of a conventional transmission, the wheel motor car does not suffer losses in the transmission. We determined the transmission efficiency in the central motor drivetrain to be 0.86 ± 0.07 (in Section 3.1). Corrected for lack of transmission losses, the electricity consumption of a wheel motor car with a 90% efficient electric motor is 89 ± 19 Wh km^{-1} on an SAE J1634 drive cycle. This is 7–21% lower than a central motor car.

A 58 kW motor for the wheel motor drivetrain provides less than the 74 kW output of the reference car, but its performance should be at least equivalent, as the reference ICE produces around 55 kW at the wheels (after transmission losses) with less torque.

Production costs

Wheels with a motor in the hub have a higher weight than normal wheels, so a specific sub-frame is installed that supports the wheel motor and its suspension. Some extra parts are also needed to produce a wheel motor drivetrain such as cables, software and special mounting parts. These are grouped under auxiliaries.

At present, production costs for a 58 kW wheel motor set for a 5-seater compact car is €17,245 [58]. A breakdown of the production costs is shown in Table 9.

A wheel motor differs from a common permanent magnet motor only in size and shape. Therefore, we assume that at 100,000 sets, the costs of producing a wheel motor are the same as producing a normal permanent magnet motor (see Section 3.2). We assume that the auxiliaries and the sub-frame continue to have the same share of production costs as the electric motor and controller.

Lifetime, maintenance and repair

M&R of wheel motor drive trains is difficult to estimate. There are a handful of wheel motor cars on the road today. The wheel itself is the only moving part in a wheel motor, which should reduce M&R costs compared to central motor cars with a transmission, but the motor is subject to vibrations that would be dampened by the car's suspension in a central motor configuration which could increase wear. As with central electric motors, it is expected that M&R costs will decline when there is more experience with a wheel motor. As with central motor drive trains, we assume that MRT costs are the same as those of reference car.

3.4. *Downscaling the electricity generation device*

One benefit of the series hybrid drivetrain is the possibility of downscaling the electricity generation device, compared to the engine of the reference ICE drivetrain. The maximum power that the reference car generates is 74 kW, used at maximum acceleration or at very high velocity of the car (>160 km h^{-1}). In a central motor series hybrid, the electric motor also has a maximum power of 74 kW.

However, the maximum power is only used in short periods of acceleration and for driving faster than is legally allowed in most places. In hybrid cars, a battery complements the generator for peak loads. Therefore, the generator only needs to deliver the electricity to sustain maximum cruising speed, around 120 km h^{-1}.

The amount of electricity needed to drive a car at a constant velocity of 120 km h^{-1} is the sum of rolling resistance, drag, transmission losses and motor losses of the car (see Section 3.1). The sum of rolling resistance and drag for the reference car at a constant velocity of 120 km h^{-1} is around 20 kW, but increases rapidly with higher speed due to drag (see Table 10). Including losses in

Table 9
Production costs of wheel motors, for a single set of two motors, 100 sets [58] and extrapolated to >200k motor $year^{-1}$ production volume.

	Single set (€)		100 sets (€)	>100k sets $year^{-1}$ (€)
TheWheel SM 450	11,714	68%	6488	810 ± 228
Auxilliaries	1228	7%	680	166 ± 47
Sub-frame	2156	13%	1194	292 ± 82
Controller	2147	12%	1189	1066 ± 61
Total	17,245		9551	2335 ± 362

Table 10

Hybrid drive train energy requirements at various speeds, using reference car characteristics (C_{rr} = 0.01, mass = 1306 kg, C_d = 0.321, A = 2.1 m^2). Electricity consumption does not include charge/discharge or AC conversion losses.

	Speed (km h^{-1})				
	50	80	100	120	140
Rolling resistance (kW)	1.8	2.9	3.6	4.3	5.0
Air resistance (kW)	1.1	4.5	8.8	15.2	24.2
Total resistance (kW)	2.9	7.4	12.4	19.5	29.2
Transmission efficiency	0.86	0.86	0.86	0.86	0.86
Power to drivetrain (kW)	3.3	8.5	14.3	22.6	33.8
PCE + motor efficiency	0.90	0.90	0.90	0.90	0.90
Auxiliaries draw (kW)	0.3	0.3	0.3	0.3	0.3
Power from source (kW)	4.0	9.8	16.2	25.4	37.8
Combined drivetrain efficiency	0.78	0.78	0.78	0.78	0.78
Electricity consumption (Wh km^{-1})	80	122	162	212	270
σ in power from source (kW)	0.31	0.79	1.32	2.09	3.12
σ in power to drivetrain (kW)	0.28	0.71	1.19	1.88	2.81

the transmission, the load in a central motor hybrid at 120 km h^{-1} is around 30 kW.

General Motors use a 53 kW engine-generator in their Volt series hybrid. To have similar reserve capacity, and allow sustained speeds of over 140 km h^{-1}, we use a 53 kW engine-generator for the central motor hybrid. The engine-generator can be downscaled further to 46 kW for the wheel motor hybrid, because the wheel motor drivetrain does not suffer efficiency losses in the transmission.

3.5. Diesel generator

A diesel engine-generator is a diesel powered ICE that drives an electricity generator. The electricity that is generated is fed to the motor controller that distributes electricity either to the battery or to the motor directly.

An engine-generator with batteries can be operated at higher efficiency than an engine that drives the wheels of a car directly, because the engine load and speed can be kept such that the engine runs constantly at or near maximum efficiency while the battery provides power for sudden variations in power demand.

Efficiency and fuel consumption

The efficiency of an engine-generator depends on the load at which it is operated. The generator has an efficiency of 90–95%, so most of the energy losses in an engine-generator are in the diesel ICE. Maximum efficiency of the ICE is approximately 40% [59]. Accounting for start-up or operations at lower than maximum efficiency, we assume an overall efficiency of 33% [58,60].

An efficiency improvement in the ICE can have a large effect on diesel engine-generator efficiency. For consistency however, we assume the same net status quo development as with the diesel engine in a reference drivetrain.

Fuel consumption depends on how much electricity an electric car uses. One litre of diesel contains 36 MJ and generates 3.3 kWh$_e$.

Production costs

At present, a 42 kW diesel engine-generator costs €3143 and this technology is quite mature [57]. If we use the electric motor costs of the previous section and component breakdown from JRC, the ICE in the generator has a cost of €1500 + 25 € kW$_e$$^{-1}$. We add €125 for a fuel tank and €730 for exhaust gas treatment to the cost of the engine-generator [20].

Using this data, and assuming the uncertainty in costs is in the electric motor only, we estimate a 46 kW$_e$ diesel generator to power a wheel motor car at a cost of €4500 ± 200. We estimate a 53 kW$_e$ diesel generator to power a central motor car at a cost of €4800 ± 200. We assume the controller is integrated with the controller of the electric motor(s) that drive(s) the wheels.

Lifetime, maintenance and repair

An engine-generator used in stationary applications has an average lifetime of 15,000 h at full load [60], far exceeding the lifetime of the car. Over the equivalent lifetime of a car, a normal engine-generator needs little maintenance. Normal maintenance is performed every 500 h of operation. Over the 6000-h lifetime of the car that means approximately 11 times. Maintenance consists of changing the oil and all filters. This costs approximately €140 including labor [60]. Total M&R costs over the lifetime add up to €1540.

An ICE that drives a car directly must be able to go from idling to maximum power in a few seconds and back. This causes large temperature differences in the ICE and puts stress on the ICE. These differences in load cause wear in an ICE. In urban traffic or traffic jams in particular, this can lead to a shorter lifetime or higher M&R costs for the ICE. An ICE that drives an electricity generator is stressed less, because the load is controlled electronically and more constant. This should lead to lower M&R costs for the ICE. However, the series hybrid drive train as a whole has more parts than the direct ICE drive train. We therefore assume that total MRT costs are equal to the diesel reference car MRT of 4.3 €ct km^{-1}.

3.6. Electricity storage

There are four important factors that determine the attractiveness of electricity storage devices (ESDs): cost per unit (€), lifetime (h), specific power (kW kg^{-1}) and specific energy (kWh kg^{-1}).

Total weight and price of ESDs also depend on the design goals for the vehicle. For series hybrid cars, there is no universal goal. Some argue that the batteries must withstand peak load for a few seconds only to assist the engine-generator while accelerating. On the other hand, if a car has to deliver peak load for a prolonged period of time, for instance climbing a long hill, it needs enough storage capacity to last at least until the top of the hill.

Others demand long driving ranges in battery mode so the car can be used as a plug-in hybrid and be charged from the electricity grid.

Lead-acid batteries and ultracapacitors were found to have insufficient specific energy, which would lead to excessive weight and volume for the battery pack. Many contemporary hybrid cars use nickel-metal hydride (NiMH) batteries, but future cost reductions are limited by the price of nickel [23]. Safety concerns (risk of thermal runaway) have been a major reason for using NiMH batteries in cars instead of Li-ion batteries. New materials in the latest

Table 11
Approximate properties of modern Li-ion batteries.

Manufacturer	Name	Sp. energy (Wh kg^{-1})	Sp. power (W kg^{-1})	Pack cost (€ kWh^{-1})	Cycle life
Valence[a]	UEV-18XP	90	1200	1000	2000
A123 Systems[b]	26,650 (cell)	110	3000	1400	2000
Altairnano[c]	Nanosafe (cell)	90	3000	1600	10,000

[a] *Source*: Refs. [66,67].
[b] *Source*: Refs. [61,68].
[c] *Source*: Refs. [62,69].

generation of batteries have greatly reduced or eliminated that risk [61,62]. We therefore use lithium-ion (Li-ion) batteries for storage options.

3.6.1. *Minimum capacity requirements*

The size of the battery is determined by specific power and specific energy and its purpose.

Power should be large enough to enable decent acceleration of the car. which means the battery must deliver the maximum power of the electric motor(s) in a plug-in hybrid, and at least 50% in other configurations. In case of emergency (such as a generator failure), this is enough to have the car function properly in battery-only mode for a short distance.

The capacity of the battery must be at least 1.0 kWh, to allow time for warming up of the generator or fuel cell and to provide sufficient reserves for using top speeds in emergencies. This is enough to drive 7–8 km on battery only, depending on the efficiency of the drivetrain. This is similar to a Prius (NHW20 model), which has a 1.3 kWh NiMH battery pack and the Civic hybrid, which has a 0.7 kWh NiMH battery pack.

If the car is to be used as a plug-in hybrid, the size of the battery depends on the preference of the consumer. Around 80% of the trips made by cars is smaller than 50 km [63, see also 61,49], and we therefore assume that a plug-in hybrid must be able to drive at least 50 km on the batteries. This requires a battery of 6–7 kWh, depending on the electricity consumption of the car. With that battery, 80% of trips can be driven entirely in battery mode, as can the initial part of the remaining 20% of longer trips.

A purely battery-powered electric car, without a generator for long range travel, would need a battery of 32–37 kWh to achieve a range ≥300 km.

3.6.2. *Lifetime requirements*

When a car is used as a plug-in hybrid, the battery pack must be able to withstand many deep discharges. Discharging a battery down to 20% of its capacity (80% depth of discharge (DoD)) is usually considered deep discharging. The battery pack therefore needs to be over-dimensioned by 25%, so that 80% of the battery capacity is be enough to drive 50 km. In view of recent advances in cathode and anode materials, we assume batteries can be operated between 20% and 90% charge without reducing lifespan.

The lifetime of the electric drivetrain should be at least 300,000 km. We assume that the share of trips made in battery mode translates to at most 80% of the total kilometres being driven in battery mode. Therefore the battery must last for 240,000 km. The storage device is designed for a range of 50 km, so the battery pack for a plug-in hybrid must withstand up to 4800 discharge cycles.

If the battery is only used to cover peak load, the usage will be less intensive since there is usually no need to fully discharge the battery pack. This will prolong the lifetime of the battery. NiMH battery packs used in hybrid taxis are reported to have lasted over 350,000 km [64].

3.6.3. *Li-ion batteries*

Many experts consider Li-ion batteries the most preferred battery for hybrid cars, especially for plug-in hybrid cars because of their high specific energy. Li-ion batteries have found their way to commercialization in small consumer electronics and are now being introduced in hybrid electric cars.

The technical potential for Li-ion is enormous. In laboratory experiments, Li-ion batteries have shown to be capable of many thousands of deep discharge cycles. They have a specific power of 2000 W kg^{-1} and a specific energy as high as 400 Wh kg^{-1} [62]. However, the battery must be able to withstand rapid cycling in a hybrid car, and for market introduction it is important that production costs are low.

Production costs

We found several examples of state-of-the-art battery technology. Assembling cells into a battery pack reduces the specific energy and capacity by 10–15% [65]. The properties of these batteries are listed in Table 11.

Unlike NiMH batteries, Li-ion batteries do not contain scarce materials [70,71]. For the coming decade however, it is expected that the biggest challenge will be to develop safe and low-cost Li-ion batteries with a calendar life of at least 10 years. Therefore, it is not expected that there will be a large decreases in price for the coming decade.

We assume that the Li-ion battery will cost approximately 800 € kWh^{-1}, have a specific energy of 110 Wh kg^{-1} and a specific power of 3000 W kg^{-1}. This is significantly more expensive and heavy than the cost of 140 € kWh^{-1} and specific energy of 150 Wh kg^{-1} that the US Advanced Battery Consortium set as the minimum requirement for all-electric cars [72].

Lifetime

Calendar life is an important factor for Li-ion batteries. The electrodes and the electrolyte can wear rapidly thereby reducing battery performance and capacity, especially when fully charged. At present Li-ion batteries have a calendar life of around 5 years [23].

Just like for NiMH batteries, life can be extended to hundreds of thousands cycles at low DoD [61]. Because experiments have shown that state-of-the-art Li-ion batteries can withstand 4000 [23] to 9000 [62] deep discharge cycles, it is expected that lifespan will increase to at least 5000 cycles in the coming decade. We therefore ignore the possibility that a battery pack may have to be replaced over the lifetime of a car.

3.6.4. *Series hybrid battery packs*

Table 12 shows the properties of our battery packs, calculated using the vehicle configuration in Table 13 (Section 4). For the current technology series hybrids, high specific power (see Table 11) allows for the smallest, and therefore the cheapest batteries. For the plug-in hybrid, specific power is not a limiting factor and the cheapest unit per kWh (see Table 11) is used. Plug-in hybrids also include a charger at a cost of €482 [41].

Table 12
Properties of the four ESDs now and in the future, as assumed in this study.

Drivetrain			Min. range (km)	Capacity (kWh)	Cost (€)	Weight (kg)
Central motor	Hybrid	Current	8	1.1	1737	12
Wheel motor	Hybrid	Current	8	1.1	1467	10
Central motor	Plug-in	Current	50	7.4	7546 ± 1374	83 ± 16
Wheel motor	Plug-in	Current	50	6.4	6585 ± 1291	72 ± 15
Central motor	Hybrid	Future	9	1.4	1085	12
Wheel motor	Hybrid	Future	8	1.1	851	10
Central motor	Plug-in	Future	50	7.4	6379 ± 1147	67 ± 13
Wheel motor	Plug-in	Future	50	6.4	5577 ± 1077	58 ± 12

Table 13
Vehicle configurations investigated in this study. In brackets with minimum battery required is the marginal capacity requirement (see Section 3.6.1).

Vehicle configuration	Abbreviation	Motor power	Generator/fuel cell power	Minimum battery required
ICE diesel reference car		74 kW	n/a	n/a
ICE petrol reference car		77 kW	n/a	n/a
Petrol-fuelled parallel hybrid		62 kW + 30 kW$_e$	n/a	2.9 kWh (20 km)
Central motor series hybrid	SHEV CM	74 kW$_e$	53 kW$_e$	37 kW (50%)
Wheel motor series hybrid	SHEV WM	2 × 29 kW$_e$	39 kW$_e$	29 kW (50%)
Central motor plug-in hybrid	PHEV CM	74 kW$_e$	53 kW$_e$	7.7 kWh (50 km)
Wheel motor plug-in hybrid	PHEV WM	2 × 29 kW$_e$	39 kW$_e$	5.1 kWh (50 km)
Central motor fuel cell car	FCEV CM	74 kW$_e$	53 kW$_e$	37 kW (50%)
Wheel motor fuel cell car	FCEV WM	2 × 29 kW$_e$	39 kW$_e$	29 kW (50%)

The biggest challenge for batteries in the coming decade is to reduce production costs without reducing specific capacity.

3.7. *Fuel cell*

There is a small market for mobile fuel cells, mostly proton exchange membrane (PEM) cells [24,73]. BMW, Ford, Toyota and Honda have been the most active producers, building small runs of demonstration fuel cell cars [74].

Efficiency and fuel consumption

A fuel cell has a theoretical maximum conversion efficiency of 83% [75]. In practice, fuel cell efficiency is generally lower. Efficiency depends on the workload of the fuel cell. Efficiency is highest in low- to midrange loads, and lower than 50% only at loads smaller than 10% and above 80% [20,75,76]. Therefore, we assume that the fuel cell works with a constant efficiency of 55% during a driving cycle.

In a PEM fuel cell with 55% efficiency, 1 kg of hydrogen containing 120.1 MJ generates 18.5 kWh.

Production costs

The production costs of the fuel cell are currently the most important hurdle for large-scale introduction. The most expensive parts of the fuel cell are platinum, which is used as a catalyst, the bipolar plates and the proton exchange membrane.

At present the production costs of the fuel cell are between 1000 € kW^{-1} and 1800 € kW^{-1} [24,25,73,77]. Many assessments have been made on how the production costs of the fuel cell will develop. The conclusions vary between 27–35 € kW$_e{}^{-1}$ [13] 38 € kW$_e{}^{-1}$ or more [24], 50 € kW$_e{}^{-1}$ [78,79], 294 € kWh^{-1} [80] and 50–450 € kW$_e{}^{-1}$ [81]. Assumptions have a strong influence: Tsuchiya & Kobayashi ranged between 12 and 120 € kW^{-1} [24] in 2020 after 5 million units are produced. With lower production volumes, costs could remain much higher.

We assume the current cost to be 1200 ± 200 € kW^{-1}. Based on the sources above, we assume long term production costs to be 110 ± 49 € kW^{-1}, contingent on large production volumes. This is roughly equal to the cost of diesel generators and a reduction of over 90% of the current costs.

Lifetime, maintenance and repair

Under ideal circumstances current PEM fuel cells are capable of operating for 20,000 h. Putting a fuel cell through many start/stop cycles has no significant negative influence on the lifetime [73]. However, dirty air from a city, hydrogen that is not clean or operating at full load for prolonged periods can reduce the lifespan of a fuel cell. If the voltage that the fuel cell delivers is 10% lower than the voltage in the beginning of the life, the fuel cell is considered worn [73]. The minimum lifetime of a fuel cell under full load is approximately 2000 h. We assume that the fuel cell uses clean hydrogen and rarely operates at full load, extending the lifetime of the fuel cell to that of the car (9000 h, Section 2.2).

3.8. *Hydrogen storage*

The energy density of hydrogen under atmospheric pressure at room temperature is very low at 0.0108 MJ l^{-1}, compared to 36 MJ l^{-1} for diesel. This necessitates special storage methods. The only viable storage option at this moment is compressed gaseous hydrogen (CGH_2) [82,17]. This situation is expected to remain into the near future [17]. A full tank is 4.2 kg for a central motor car and 3.6 for a wheel motor car, with storage pressure between 35 and 70 MPa. JRC estimates the price of such a tank to reach 575 € kg^{-1} H_2 and to weigh 56 kg [20].

4. Cars

We constructed 15 vehicle configurations using our data: 3 reference cars, 6 current series configurations and 6 future configurations. The requirements are the same for current and future configurations, and difference is in the vehicle costs. Our configurations are summarised in Table 13.

We compare these configurations to each other and the reference diesel and petrol cars, as well as a petrol-fuelled parallel hybrid.

4.1. *Fuel consumption and CO_2 emissions*

Table 14 shows the tank-to-wheel (TTW) and well-to-wheel (WTW) fuel consumption of our vehicle configurations. The results

Table 14
TTW fuel consumption, range on 36 MJ (equivalent of 1 l of diesel) in the tank or battery, and WTW energy consumption. Plug-in hybrids have the same fuel consumption as regular series hybrids when driving on diesel.

Vehicle configuration	Fuel	Fuel consumption (MJ km^{-1})	Range (km) on 36 MJ	Primary energy used (MJ km^{-1})
Reference diesel	Diesel	1.77	20	2.01 ± 0.4
Reference petrol	Petrol	1.90	19	2.19 ± 0.55
Parallel hybrid	Petrol	1.51	24	1.74 ± 0.44
SHEV central motor	Diesel	1.16 ± 0.23	31 ± 6	1.32 ± 0.37
SHEV wheel motor	Diesel	1.00 ± 0.21	36 ± 8	1.16 ± 0.34
PHEV central motor	Grid electricity	0.43 ± 0.08	83 ± 16	1.13 ± 0.26
PHEV wheel motor	Grid electricity	0.37 ± 0.08	97 ± 20	0.98 ± 0.24
FCEV central motor	Hydrogen	0.70 ± 0.14	52 ± 10	1.04 ± 0.21
FCEV wheel motor	Hydrogen	0.60 ± 0.13	60 ± 13	0.90 ± 0.2

Table 15
Greenhouse gas emissions from our vehicle configurations in g CO_2 equivalent km^{-1}. Note that total emissions may also be sharply reduced by other means, such as sustainable biofuels.

Vehicle configuration	Fuel	TTW emissions (g km^{-1})	WTT emissions (g km^{-1})	Total emissions (g km^{-1})
Reference diesel	Diesel	131	25 ± 5	156 ± 5
Reference petrol	Petrol	140	22 ± 6	163 ± 6
Parallel hybrid	Petrol	112	18 ± 4	129 ± 4
SHEV central motor	Diesel	87 ± 17	16 ± 5	103 ± 20
SHEV wheel motor	Diesel	75 ± 16	14 ± 4	89 ± 19
PHEV central motor	Grid electricity		0–69	0–69
PHEV wheel motor	Grid electricity		0–60	0–60
FCEV central motor	Hydrogen		0–131	0–131
FCEV wheel motor	Hydrogen		0–115	0–115

are dominated by the efficiency of the on-board energy converters: 33% for the diesel generator, 55% for the fuel cell, and 86% for the battery charger (from the grid). The WTW uncertainties include uncertainty in marginal oil refining (20% for diesel, 25% for petrol) [20], electricity generation at an assumed 44 ± 5% efficiency and 86% grid efficiency [51], and differences between various ways of hydrogen production [83,20,84].

Our calculations show a reduction in fuel consumption of 44% for a wheel motor series hybrid compared to the reference diesel car. Our only known empirical comparison is from an wheel motor city bus that achieved a certified reduction of 62–69% when compared to an equivalent regular diesel bus in a SORT 2 driving cycle that mimics light urban traffic [85–87].

Table 15 shows the emissions of greenhouse gasses from our vehicle configurations. The GHG emissions depend on the emissions of the car (TTW) and the emissions made in producing the required diesel, petrol, hydrogen or electricity (well-to-tank – WTT). We used TTW emission factors of 73.2 g CO_2 MJ^{-1} diesel and 73.3 g CO_2 MJ^{-1} petrol and WTT emission factors of 14 ± 3 g $CO_{2\,\mathrm{equivalent}}$ MJ^{-1} diesel and 12 ± 3 g $CO_{2\,\mathrm{equivalent}}$ MJ^{-1} petrol [20]. For hydrogen and electricity, there are no TTW emissions, and WTT emissions vary by the source. WTT emissions are assumed to be 0 if generated from solar or wind power, and up to 467 ± 59 g CO_2 kWh^{-1} for electricity and 158 g MJ^{-1} H_2 if generated from coal without carbon capture and sequestration (CCS) [based on 84]. Emissions from electricity assume the same suppliers used to calculate electricity price, fuelled with around 20% coal and 45% natural gas, corrected for grid losses.

The series hybrid cars generate less CO_2 than the reference cars: well-to-wheel, the diesel series hybrid produces less than 60% of the CO_2 of the reference diesel car. The plug-in hybrid using electricity has lower CO_2 emissions than any of the diesel-fuelled cars: around 69 g km^{-1} for a central motor and around 60 g km^{-1} for a wheel motor configuration.

Table 16
Vehicle production costs (in € including VAT). Uncertainty depends on the assumptions about conversion efficiency and motor cost.

Vehicle configuration	Platform	Electrical drive	ICE/generator/FC	Battery	Total (€)
Reference diesel	15725	0	5635	0	21,360
Reference petrol	15435	0	3725	0	19,160
Parallel hybrid	15435	3662	2983	2826 ± 0	24,906 ± 0
SHEV CM now	15725	4375 ± 747	4823 ± 211	1737	26,659 ± 776
SHEV WM now	15725	9551	4546 ± 188	1467	31,289 ± 188
SHEV CM future	15725	4375 ± 747	4823 ± 211	1085	26,008 ± 776
SHEV WM future	15725	2335 ± 724	4546 ± 188	851	23,456 ± 748
PHEV CM now	15725	4375 ± 747	4823 ± 211	7546 ± 1374	32,469 ± 1578
PHEV WM now	15725	9551	4546 ± 188	6585 ± 1291	36,407 ± 1304
PHEV CM future	15725	4375 ± 747	4823 ± 211	6379 ± 1147	31,302 ± 1385
PHEV WM future	15725	2335 ± 724	4546 ± 188	5577 ± 1077	28,183 ± 1312
FCEV CM now	15725	4375 ± 747	66,015 ± 10,600	1737 ± 132	87,852 ± 10,627
FCEV WM now	15725	9551	57,296 ± 9200	1467 ± 204	84,039 ± 9202
FCEV CM future	15725	4375 ± 747	8245 ± 2588	1085	29,430 ± 2694
FCEV WM future	15725	2335 ± 724	7156 ± 2246	851 ± 119	26,066 ± 2363

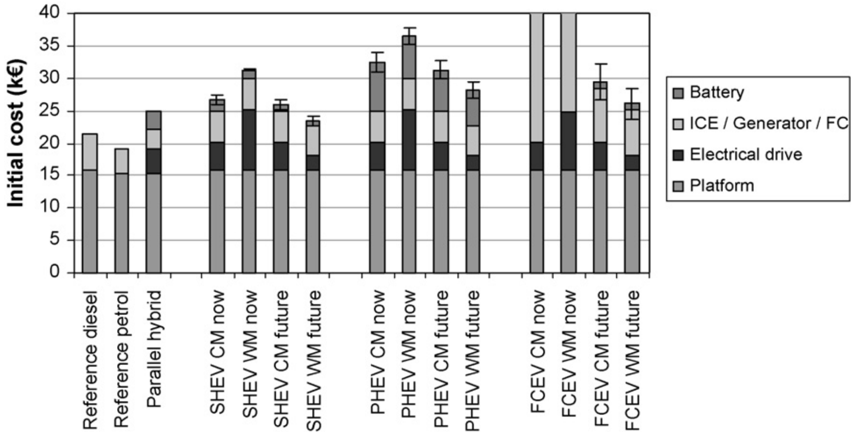

Fig. 3. Vehicle production costs (including VAT). Error bars indicate uncertainty in total production costs, given the assumptions about conversion efficiency, and motor cost.

The production of the fuel and/or electricity has as much influence on transport emissions as the efficiency of the drive train. However, calculating the impact of alternatives, such as sustainable biofuels and CCS, requires a context that is beyond the scope of this article.

4.2. Production costs

Table 16 and Fig. 3 show the total production costs per component and the total production costs of the car. Total production costs are the lowest for ICE drivetrains. Current production costs of fuel cell stacks are an order of magnitude higher than those of competing drivetrains.

The production costs of any of the hybrid cars will remain higher than the cost of an ICE car, because of the additional components (mostly electric motors).

5. What does it cost to drive?

5.1. Variable costs

Table 17 shows the variable costs of driving our vehicle configurations, with fuel prices including VAT but no excise duty. Because we assumed no net efficiency gains in the drive trains and stable fuel prices, the current and future models have the same results. The total variable costs for plug-in hybrids are calculated with driving 80% on electricity and 20% on diesel.

The variable costs for the wheel motor drivetrains are lower than those for the central motor drivetrain, whether electricity is generated by a fuel cell, by a diesel generator or drawn from the grid. Variable costs of the ICE powered by petrol are the highest. The fuel cell car has the highest variable cost among the configurations with fully electric drivetrains.

5.2. Total cost of ownership

We calculate the TCO assuming the cars are driven 20,000 km year^{-1}, using a 10-year depreciation period and a 5% social discount rate. Table 18 and Fig. 4 show the TCO of our configurations with VAT only.

These results are dominated by the cost of purchasing the car, which are 60–90% of the TCO. The TCO of all of our hybrid configurations are higher than those of the reference cars, with the sole exception of the future wheel motor series hybrid. There we may conclude that the current generation of hybrid cars cannot compete strictly on costs with regular diesel or petrol cars without additional support.

5.3. Tax incentives

From the perspective of motorists, the financial attractiveness of hybrid cars is influenced by tax incentives, as well as a higher implicit discount rate [37]. Many countries have tax incentives for low-emission cars and tax situations are country-specific. We use a 10% consumer discount rate, which is closer to consumptive credit loan interest rates, and the Dutch tax context as an example. In the Netherlands, three forms of tax affect TCO of a car:

- Fuel excise duty, an additional 0.38 € l^{-1} on diesel, 0.69 € l^{-1} on petrol and 0.1085 € kWh^{-1} on electricity in 2009 [46].
- Tax on light duty cars and motorcycles (BPM in Dutch), which is 45.2% of the car price, modified for the type of engine and fuel consumption in seven categories. BPM is further reduced for hybrid cars, and plug-in hybrids and hydrogen-fuelled cars are exempt entirely. BPM is a one-time payment.
- Road tax, depending on the type of fuel and weight of the car. Road tax is reduced by half for diesel-fuelled cars with TTW emis-

Table 17
Variable costs (including VAT). Uncertainty derives from the assumptions on efficiency.

Vehicle configuration	MRT	Diesel/petrol	Electricity (grid)	Hydrogen	Total (€ km^{-1})
Reference diesel	0.043	0.041			0.084
Reference petrol	0.042	0.044			0.086
Parallel hybrid	0.042	0.035			0.077
SHEV central motor	0.043	0.027 ± 0.005			0.070 ± 0.005
SHEV wheel motor	0.043	0.023 ± 0.005			0.066 ± 0.005
PHEV central motor	0.043	0.027 ± 0.005	0.012 ± 0.002		0.058 ± 0.003
PHEV wheel motor	0.043	0.023 ± 0.005	0.011 ± 0.002		0.056 ± 0.003
FCEV central motor	0.043			0.031 ± 0.006	0.074 ± 0.006
FCEV wheel motor	0.043			0.027 ± 0.006	0.070 ± 0.006

Table 18
Total cost of ownership (TCO, € year^{-1}) breakdown of our model configurations using a 5% social discount rate and VAT only, driving 20,000 km year^{-1} and depreciating over 10 years.

Vehicle configuration	Annualised purchase	MRT	Diesel/petrol/H_2	Electricity	TCO (€ year^{-1}, VAT only)
Reference diesel	2766	866	813	0	4445
Reference petrol	2481	834	899	0	4214
Parallel hybrid	3225 ± 0	832	713	0	4770 ± 0
SHEV CM now	3453 ± 100	866	534 ± 104	0	4852 ± 145
SHEV WM now	4052 ± 24	866	462 ± 98	0	5379 ± 101
SHEV CM future	3368 ± 100	866	534 ± 104	0	4768 ± 145
SHEV WM future	3038 ± 97	866	462 ± 98	0	4365 ± 138
PHEV CM now	4205 ± 204	866	107 ± 21	195 ± 38	5372 ± 213
PHEV WM now	4715 ± 169	866	92 ± 20	168 ± 36	5841 ± 178
PHEV CM future	4054 ± 179	866	107 ± 21	195 ± 38	5221 ± 189
PHEV WM future	3650 ± 170	866	92 ± 20	168 ± 36	4776 ± 179
FCEV CM now	11,377 ± 1376	866	617 ± 120	0	12,860 ± 1381
FCEV WM now	10,883 ± 1192	866	533 ± 113	0	12,282 ± 1197
FCEV CM future	3811 ± 349	866	617 ± 120	0	5294 ± 369
FCEV WM future	3376 ± 306	866	533 ± 113	0	4775 ± 326

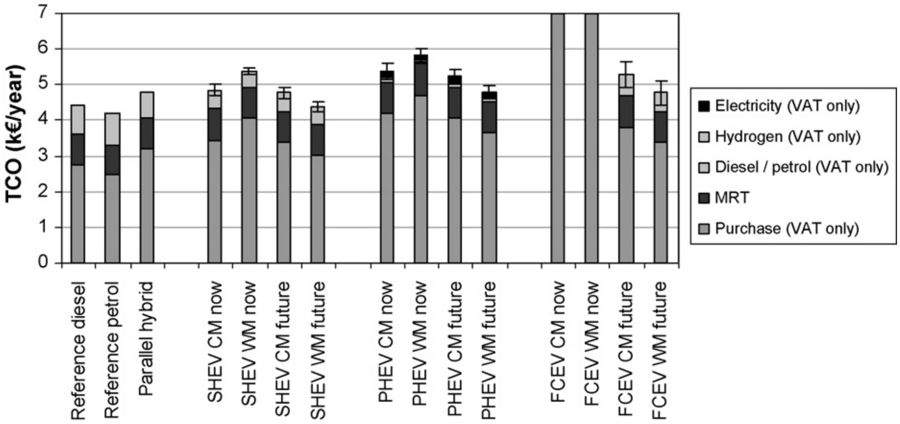

Fig. 4. Total cost of ownership (TCO, k€ year^{-1}) breakdown of our model configurations using a 5% social discount rate and VAT only, driving 20,000 km year^{-1} and depreciating over 10 years.

sions of less than 95 g CO_2 km^{-1}. Road tax is paid at regular time intervals.

Fig. 5 shows that the Dutch tax context is advantageous to our series hybrid configurations and future fuel cell cars.

Mass produced parallel hybrid cars, and series and plug-in hybrid cars with a central motor have equal or lower TCO than the reference diesel car in the current Dutch tax context. TCO of current central motor hybrid cars is slightly higher.

While future fuel cell cars have the lowest TCO in the current tax context, it should not be taken for granted that this situation will be reached, as the current fuel cell cars have much higher TCO and the reduction in the cost of fuel cells depends on large-scale production. Some in the car industry do not expect large-scale penetration of fuel cell cars until 2035 [88]. Furthermore, the tax incentives for stimulating fuel efficient cars may change as hybrid and/or fuel cell cars break into mainstream use.

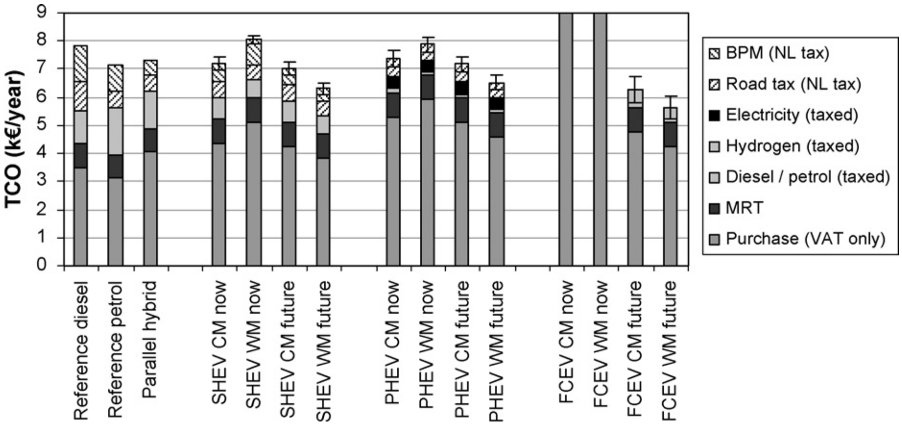

Fig. 5. Total cost of ownership (TCO, k€ year^{-1}) of our model configurations with a 10% consumer discount rate in the Dutch tax context.

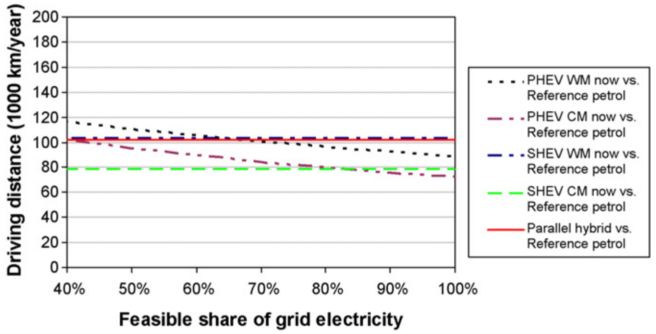

Fig. 6. Lowest TCO isopleths for current generation central motor configurations and reference cars, using a 10% consumer discount rate.

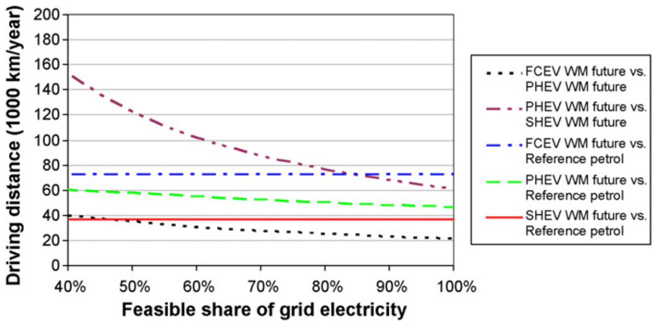

Fig. 7. Lowest TCO isopleths for future hybrid and fuel cell configurations and petrol reference.

Using a 33% discount rate and 15-year lifespan [89], the purchasing cost of the vehicle completely dominates the TCO ranking and the difference made by taxes and fuel costs fall within the uncertainty margins.

5.4. *Who can benefit from the series hybrid car?*

We showed that a series hybrid car can be operated at the lowest costs with (existing) supporting incentives. However, without such measures, the lowest TCO is found for cars with low variable costs, i.e. hybrids and plug-in cars. Variable costs depend on the distance driven in a year and, for plug-in hybrids, the share of electricity that is used instead of diesel.

When we plot the TCO for different configurations as a function of distance and electricity share in total fuel, and project the intersects in a flat plane, we obtain isopleth curves which show at which driving habits it is cheaper to switch to another configuration (break-even points).

Fig. 6 shows that the current series hybrid, though more expensive to purchase, becomes more attractive than a petrol car at 79,000 ± 9800 km year^{-1}. That large distance is due to the lower MRT costs of a petrol car, which partially offsets the lower fuel costs of the series hybrid. The difference in TCO between the central motor and wheel motor hybrid cars at this distance is less than 500 € year^{-1}, even with current production costs for wheel motors. At less than 60,000 km year^{-1}, there is no significant difference in TCO of the central motor series hybrid and parallel hybrid cars. Diesel cars, the traditional choice for those who drive more than 20,000 km year^{-1}, are found to be more expensive than a petrol car at small distances, and more expensive than a series hybrid at higher distances.

The plug-in configuration becomes more attractive than the SHEV at a >80% share of electricity and large distances, which could be mutually incompatible in the real world. However, the TCO differences between a PHEV and SHEV are fairly small and the uncertain zone around these isopleths fills the whole graph. The wheel motor PHEV also benefits less from lower fuel costs than the central motor configuration because the overall fuel consumption of the wheel motor configuration is smaller.

Fig. 7 shows that for future generations of wheel motor series hybrids, the petrol car remains attractive for those who drive fewer than 37,000 ± 3500 km year^{-1}. If our projections on cost developments hold, plug-in hybrids and fuel cell cars will be cheaper than either petrol or diesel cars when driving more than 70,000–84000 km year^{-1}, but the series hybrid has lower TCO than the fuel cell car at any relevant distance. Again, the plug-in configuration only becomes attractive at high shares of electricity and large distances.

Our findings suggest that resources be devoted to further development and commercial introduction of wheel motors and to promote the use of hybrid cars among groups such as taxi drivers and others who drive high distances.

6. Discussion

6.1. *Drivetrain efficiency*

With regards to the fuel consumption, our calculations for the electric drivetrain depend on very few measurements of very different existing cars, and our transmission efficiency result of ~0.86 treats the transmission as a black box.

We also assumed 33% engine-generator efficiency, and 90% efficient electric motors, which is generally true only for constant speeds. Average electric motor efficiency can drop to 84% in parallel hybrid configurations, where a small electric motor is used almost exclusively for acceleration [20].

We also treat fuel consumption results from the SAE J1634 drive cycle (used for electric cars, and to derive our platform fuel consumption) as equivalent to those achieved with the NEDC (used for the reference cars). Furthermore, we assume that average real-world driving conditions are properly represented by the NEDC and SAE J1634 drive cycles. A driver who drives at more constant speeds and makes fewer stops will benefit less from a hybrid car. Driving patterns have particularly strong impact on the benefits of a series hybrid compared to an ICE car and to fuel consumption in general.

These limitations explain why our central motor series hybrid configurations have lower average fuel consumption than a parallel hybrid, while other authors assert fuel consumption should be similar [32,90]. However, even if the central motor series hybrid is not an improvement on the parallel hybrid, wheel motors reduce fuel consumption significantly by removing the transmission.

Our medium term calculations do not include potential further efficiency improvements to drivetrains. However, total fuel consumption is 4–19% of TCO, and the effect of efficiency gains on TCO is therefore similar to those variations in oil prices and smaller than those of (implicit) consumer discount rates.

6.2. *Weight*

We did not correct fuel consumption for extra weight. For cars without regenerative braking, fuel consumption increases by some 3–8% for every 10% increase in car weight [91], due to increased rolling resistance. For our series hybrids, weight increases were not included in the fuel consumption calculations. Fig. 8 shows that the weight increase for a central motor series hybrid is less than 5%, while the wheel motor hybrid is slightly lighter than the reference diesel car.

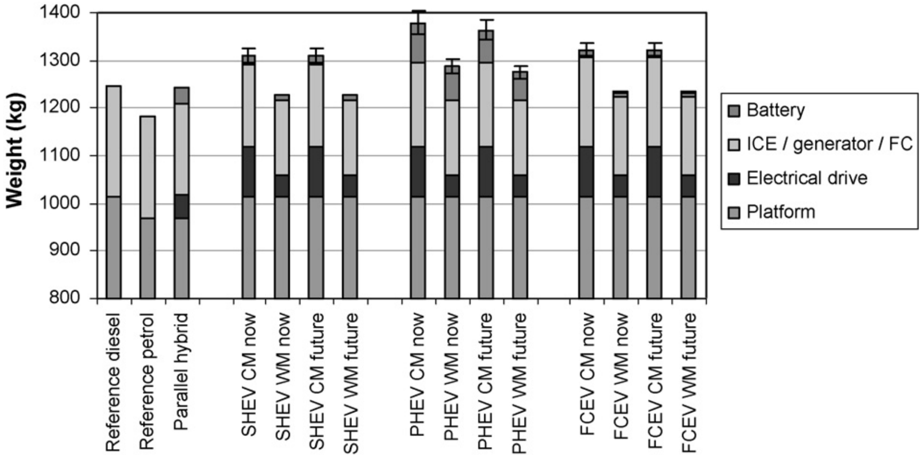

Fig. 8. Weight of our model configurations.

6.3. *Prices of fuel*

The prices of diesel and petrol are volatile. Therefore, they can have substantial influence on the TCO. To illustrate this, we increase the price of oil to $120\,\$\,\mathrm{bbl}^{-1}$, without raising the price of electricity or hydrogen, plug-in hybrids and fuel cell cars would essentially have the same TCO as series hybrids (uncertainty ranges overlap), as shown in Fig. 9. This situation is unlikely because prices of electricity and hydrogen do not move independently from oil prices, and because alternatives to diesel and petrol such as heavy crude and second generation biofuels become competitive when oil prices exceed $75\,\$\,\mathrm{bbl}^{-1}$ [84].

Lower hydrogen prices make fuel cell cars more competitive. We found estimates of costs (not commercial prices at the pump) of production and distribution of 15–36 € GJ^{-1} [22,83, and combining 17,92,84]. With fuel cell production cost of 110 € kW^{-1}, hydrogen would need to cost less than 20 € GJ^{-1} for the future fuel cell car to have a lower TCO than future series hybrids. However, current fuel cell cars cannot compete commercially even if hydrogen is provided free of charge.

The influence of driving on grid electricity on TCO is limited. The added costs for batteries in a plug-in hybrid were only compensated at high shares of electricity and high driving distance. The competitiveness of plug-in hybrids (and, by extension, electric cars) therefore mainly depends on the price of batteries.

Imposing a CO_2 tax on cars and/or fuels may also shift competitiveness. There are many ways of producing alternatives to diesel and petrol (including biofuels) as well as electricity and hydrogen, with strongly divergent GHG emissions. Because the vehicle configuration is in no way linked to the way of producing the fuel, calculating the impact of CO_2 taxes on GHG emissions from cars requires a context that is beyond the scope of this article.

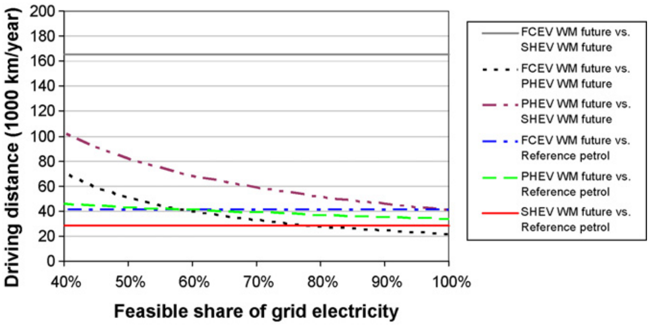

Fig. 9. Lowest TCO isopleths for current generation central motor configurations and reference cars with oil at $120\,\$\,\mathrm{bbl}^{-1}$. Recall that 80% of car trips are <50 km and could be driven on electricity in a plug-in hybrid.

6.4. *Vehicle costs and maintenance*

We found the cost of batteries would have to drop to below 300 € kWh^{-1} for the plug-in hybrid to have the same TCO (at 80% electric driving) as a regular series hybrid. This is a smaller cost reduction than estimated for fuel cells. An all-electric car with a 250 km range would almost the same TCO as a plug-in hybrid at a battery production cost of 200 € kWh^{-1}. Our incremental costs for PHEV are similar to those found in other studies that use similar assumptions on battery cost [93,94].

Cycle life of batteries has tripled (or better) in recent years, and we have assumed that the same will apply to calendar life. However, it is unclear if calendar life of state-of-the-art batteries will last the 10-year lifespan of a car. If this is not the case, the TCO must be increased by a discounted €900–1800 somewhere in the life of the vehicle. The same applies to fuel cells, with replacement costs upwards of €5100.

The uncertainties in the cost of fuel cell drivetrains are substantial, and the case can be made [14,19] that current high prices and lack of refuelling infrastructure will not allow sufficient units to be sold to reach mass production. In this case, the final cost of fuel cells will remain higher than the 110 € $\mathrm{kW_e}^{-1}$ we assumed.

The same is true in principle for wheel motors, but the TCO of a wheel motor hybrid is relatively much closer to that of a central motor hybrid, so initial cost should not be a major barrier.

Although we find substantial uncertainties regarding the production costs of the different components of drivetrains (see Table 16 in Section 4.2), their influence, except for the fuel cell, on the TCO is limited (see Table 18 in Section 5.2). The vehicle platform, MRT, fuel, and taxes all have more influence on TCO.

For a lack of experience, maintenance, repair and tires costs for series hybrids and fuel fell cars, both with central motor and wheel motors, are unclear. Because drivetrain maintenance is only a part of the total MRT costs, we expect the differences to be small. Available data show that MRT costs of existing commercial hybrid cars are equal or slightly lower than those of non-hybrid versions or similarly sized models for the same manufacturer [29]. However, our TCO comparison is quite sensitive to maintenance costs: for every MRT cost increase of 0.1 €ct km^{-1} (20 € year^{-1}), the break-even distance of the series hybrids and fuel cell car increases by 2000–5000 km year^{-1}.

6.5. Availability of data

We observe substantial uncertainty ranges in component costs and fuel consumption, caused by a shortage of freely available data on the production costs of car parts, and a lack of comparable data about fuel consumption. Our data on the production costs of wheel motors are based on the data from a single small producer.

With regard to the costs of electric motors and batteries, we assume that commercial interests keep producers from publishing transparent prices. The only way to improve the quality of this data would likely bar free publication.

7. Conclusions

We investigated the fuel consumption and costs of four diesel-fuelled series hybrid, four plug-in hybrid and four fuel cell car configurations and compared these to three reference cars.

Results indicate that series hybrid cars may reduce fuel consumption by 34–47% compared to reference petrol and diesel cars and reduce WTW GHG emissions to 89–103 g CO_2 km^{-1} using regular diesel. Series hybrid cars with wheel motors have lower weight and 7–21% lower fuel consumption than series hybrid cars with central electric motors. However, series hybrid cars currently cost €5000–10,000 more than ICE cars.

The higher purchase cost of hybrid cars means they are financially interesting for taxi drivers and others who drive more than 80,000 km $year^{-1}$. For these groups, the current generation of series hybrid would the most attractive option, even without tax incentives. Including the Dutch tax incentives, the TCO of a parallel or series hybrid is currently lower than that of a diesel car even when driving around 20,000 km $year^{-1}$.

The TCO of a wheel motor series hybrid car is currently higher than one with a central motor, but the difference is less than 500 € $year^{-1}$ at driving distances where the series hybrid is preferred over a petrol car. In the future, wheel motors are projected to be the cheapest and most efficient drivetrain. The possibility to use wheel motors is the main benefit of a series drivetrain.

The fuel cell car is currently uncompetitive by a large margin. If, despite their current financial unattractiveness for use in cars, the production of fuel cells would increase so that the costs come down by 90%, series hybrids would still have slightly lower total cost of ownership. Plug-in hybrids are competitive only when driving large distances on electricity and/or if cost of batteries come down substantially. Plug-in hybrids may reduce WTW GHG emissions to 60–69 g CO_2 km^{-1}, assuming emissions for generating electricity of around 467 g CO_2 kWh^{-1}.

We recommend benchmarking fuel consumption using a standardised vehicle platform and a single representative drive cycle to clarify the differences in efficiency between transmission attached to ICE and electric drivetrain, and between central motor and wheel motors. If this cannot be done using real engines, the results can be simulated using engine maps for the ICE and electric motors.

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