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Energy use, cost and CO_2 emissions of electric cars

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ABSTRACT

We examine efficiency, costs and greenhouse gas emissions of current and future electric cars (EV), including the impact from charging EV on electricity demand and infrastructure for generation and distribution.

Uncoordinated charging would increase national peak load by 7% at 30% penetration rate of EV and household peak load by 54%, which may exceed the capacity of existing electricity distribution infrastructure. At 30% penetration of EV, off-peak charging would result in a 20% higher, more stable base load and no additional peak load at the national level and up to 7% higher peak load at the household level. Therefore, if off-peak charging is successfully introduced, electric driving need not require additional generation capacity, even in case of 100% switch to electric vehicles.

GHG emissions from electric driving depend most on the fuel type (coal or natural gas) used in the generation of electricity for charging, and range between 0 g km^{-1} (using renewables) and 155 g km^{-1} (using electricity from an old coal-based plant). Based on the generation capacity projected for the Netherlands in 2015, electricity for EV charging would largely be generated using natural gas, emitting 35–77 g $CO_{2\,eq}$ km^{-1}.

We find that total cost of ownership (TCO) of current EV are uncompetitive with regular cars and series hybrid cars by more than 800 € $year^{-1}$. TCO of future wheel motor PHEV may become competitive when batteries cost 400 € kWh^{-1}, even without tax incentives, as long as one battery pack can last for the lifespan of the vehicle. However, TCO of future battery powered cars is at least 25% higher than of series hybrid or regular cars. This cost gap remains unless cost of batteries drops to 150 € kWh^{-1} in the future. Variations in driving cost from charging patterns have negligible influence on TCO.

GHG abatement costs using plug-in hybrid cars are currently 400–1400 € $tonne^{-1}$ $CO_{2\,eq}$ and may come down to −100 to 300 € $tonne^{-1}$. Abatement cost using battery powered cars are currently above 1900 € $tonne^{-1}$ and are not projected to drop below 300–800 € $tonne^{-1}$.

1. Introduction

Worldwide, more than 90% of the transport sector is powered by fuels derived from oil. However, the consumption of diesel and petrol is considered problematic due to costs of oil, doubts about of security of oil 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 the transport sector, alternatives like biofuels and more efficiency (hybrid) cars are used in increasing volume and numbers [5,6]. The cost and potential emission benefits of biofuels and hybrid vehicles have been pointed out in numerous studies (c.f. [7–14]). For example, costs of sugar cane ethanol are already competitive with traditional fuels, and second generation ethanol can become so in the near future. In addition, using biofuels reduces emissions of GHG when produced sustainably, and also reduces emissions of other air pollutants. Fuel consumption and therefore emissions from efficient hybrid cars are lower than those from traditional cars. Drawbacks of these alternatives concern the uncertainty about the available supply of sustainable biofuels, the currently higher costs of hybrid vehicles, and the remaining tailpipe emissions of GHGs and air pollutants.

Electric driving is also considered a promising alternative and has been advocated for decades [15–17]. It does not cause any tailpipe emissions but may cause emissions of GHGs and other air pollutants, depending on the mix of electricity sources used. Three

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Abbreviations: BPEV, battery powered electric vehicle; CHP, combined heat and power; CM, central motor; GHG, greenhouse gas; ICE, internal combustion engine; JRC, Joint Research Centre (directorate of the European Commission); MRT, maintenance, repair and tires; NGCC, natural gas combined cycle; O&M, operation and maintenance; PHEV, plug-in hybrids electric vehicle; SHEV, series hybrid electric vehicle; SUV, sports utility vehicle; TCO, total cost of ownership; TTW, tank to wheel; VAT, value added tax; WM, wheel motor; WTT, well to tank; WTW, well to wheel.

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basic designs for electric driving can be distinguished: the first is a series-parallel hybrid car, which has an internal combustion engine (ICE) and an electric motor that are both connected to the wheels and supplement each other when needed (see [18]). The second is a plug-in series hybrid vehicle (PHEV), which has a small battery for trips up to approximately 50 km and a generator using an ICE to provide power for long range driving. The third is a fully battery powered electric vehicle (BPEV), which has a large battery for longer trips (200–300 km). The series-parallel car has been in use for over a decade and is not considered in detail in this study. PHEV and BPEV are currently introduced into the market: major car manufacturers all over the world are working on new models [19–23]. Electric utilities and governments in various countries support the emergence of this market (e.g. [24]).

The additional costs of plug-in hybrid and fully electric cars compared to regular ICE cars largely depend on the high costs of batteries [13,25,26]. With current battery costs in the order of €1000 kWh^{-1}, plug-in cars with a battery-powered range of 50 km or more (which requires a battery of ±7 kWh) are prohibitively expensive. However, to determine the total cost of owning and driving an EV in the short term and to determine prospects on longer term, requirements for additional electricity generation and distribution, and technological improvements and cost reductions should be taken into account [27–29].

It has been projected that an electric vehicle increases the electricity consumption of a household in an industrialised country by 50% [30]. Introducing a large number of electric vehicles therefore introduces new challenges, like building infrastructure for charging, improving the electricity distribution grid, and taking care of legal and privacy issues regarding coordinated ‘smart’ charging systems. The extent of these challenges is strongly determined by the timing and pattern of charging EVs [31,32].

We wish to determine whether large scale use of EV is or can become feasible from a techno-economic perspective, and if so, under what conditions. We therefore examine efficiency and costs of current and future EV, as well as their impact on electricity demand and infrastructure for generation and distribution, and thereby on GHG emissions. Energy used and emissions from manufacture of EV are left outside the scope of this study (c.f. [33]).

Earlier studies have addressed some of these issues separately. Some important well-to-wheel (WTW) studies do not include PHEV and BPEV cars [7,34,35]. Campanari et al. [36] and Silva et al. [26] focussed on efficiency of EV using current technology and did not take uncertainty in various chain aspects into account. Van Vliet et al. [13] and Shiau et al. [25] included sensitivity analysis on various factors affecting EV performance, including battery cost and vehicle weight, but did not take charging patterns into account.

Earlier studies have also only partially addressed how increased electricity demand could be catered for. A study for Sweden assumed that only renewable energy sources are used for electricity generation [37]. A study for Germany used inflexible charging scenarios, not taking options for coordinated charging into account to smooth demand [31]. Studies for the US assumed that the capacity factors of power generation sources will remain the same with high numbers of EVs [32], or just evaluate how many cars the current grid can support [38]. Other studies did not take into account the load pattern of existing demand [16,39].

We therefore examine the feasibility of electric driving taking into account not only drivetrain choices, but also driving patterns, changes in the electricity mix, charging patterns, and energy losses in relevant parts of the WTW chain. There are three main aspects to this analysis:

Determine the effect of EV charging patterns on household and total electricity demand.

Derive GHG emissions and costs of charging of EVs in the 2015 Dutch context and beyond.

Compare GHG emissions and costs of PHEV and BPEV with those of regular cars.

We briefly discuss methods in Section 2, present data used in Section 3, present results in Section 4, discuss the applicability of our results in Section 5 and give a summary and conclusion of our findings in Section 6.

2. Methods

The car class we focus on is the compact 5-seater. It includes the Volkswagen Golf, Ford Focus, Renault Megane, Toyota Corolla and Opel Astra. We compare EV configurations to a regular petrol car, diesel car, parallel hybrid car and SHEV. Vehicle configurations are composed using the methodology and data described in Van Vliet et al. [13].

In order to compare vehicles, we use the same platform for all vehicle configurations and only exchange the drivetrain as is also done in Weiss et al., the EU Joint Research Centre (JRC) and Van Vliet et al. [40,7,13]. The vehicle platform is defined as a vehicle without the drivetrain and includes the chassis, suspension, wheels, doors, seats, windows, and assembly. This platform weighs 1016 kg, costs €15700, and is powered by a 74 kW ICE or equivalent [7]. The drivetrain consists of the engine and the transmission connecting it to the wheels. An EV can be designed with a single central motor connected to the wheel via a transmission like in a regular ICE car, or with electric motors built into the rims of the wheel [13].

Series hybrid vehicles (SHEV) and BPEV represent opposite ends of an electric drivetrain spectrum. The SHEV uses an ICE exclusively to power the electric motor, the BPEV uses a battery. A series drivetrain PHEV is somewhere within this spectrum. It uses a battery for short range driving, and switches to ICE-generated electricity when the battery is depleted.

Total WTW energy consumption in an EV (E_{total}) is expressed in $\mathrm{MJ\,km}^{-1}$ determined as follows:

$$E_{total} = E_{resis\tan ce}/\eta_{transmission}/\eta_{motor}/\eta_{fuel\ \sup ply} \quad (1)$$

where $E_{resistance}$ is the mechanical energy required to move the car against resistance from inertia, wind and tire friction. Losses accumulate through the WTW chain, where $\eta_{transmission}$ is the transmission efficiency, η_{motor} is the efficiency of the electric motor or ICE motor, and $\eta_{fuel\ supply}$ is the fuel supply efficiency. For a wheel motor, by definition, $\eta_{transmission} = 1$.

Fuel supply efficiency depends on whether the EV is powered by an ICE or electric motor. The well-to-tank (WTT) efficiency (η_{WTT}) is determined as follows for liquid fuels and electricity:

$$\eta_{liquid\,fuel} = \eta_{distribution} \times \eta_{fuel\,plant} \times \eta_{resource\,extraction} \quad (2)$$

$$\eta_{electricity} = \eta_{charging} \times \eta_{grid} \times \eta_{power\ plant} \times \eta_{resource\,extraction} \quad (3)$$

where $\eta_{distribution}$ is the energy used for driving distribution trucks and filling stations, $\eta_{fuel\ plant}$ is most commonly the efficiency of an oil refinery, $\eta_{resource\ extraction}$ is the efficiency of mining or farming of energy resources, $\eta_{charging}$ is efficiency of charging and discharging the battery, and η_{grid} is the efficiency of the electricity distribution grid. If solar power or wind is used, $\eta_{resource\ extraction} = 1$.

The source of electricity used for charging EVs depends on the available power capacity and existing demand pattern of households, offices, industry, and public services (such as street lighting). We determine the total costs, marginal costs, and emissions of electricity at 15-min intervals by matching dispatch of electricity generation options to the demand pattern. The demand pattern uses household or national demand and includes additional load for EV charging, depending on the EV used and the EV penetration rate.

Electricity generation capacity is ranked in a merit order on the basis of variable costs and types of units. We determine the supply mix by employing plants that are progressively higher in the merit order until demand is satiated. Combined heat and power (CHP) plants co-produce heat that must be delivered and are therefore given precedence. Base load is preferably provided by nuclear and coal-fired plants that provide constant supply with relatively low operating costs. Wind and solar power produce electricity with low operating costs but their production is not entirely predictable or controllable. Fluctuations in demand and intermittent supply are accommodated by the use of peak load capacity like natural gas-fired turbines and hydropower that can be quickly switched on or off. All power plants have limits on availability (due to maintenance and unplanned outages), so we include capacity factors for calculating average supply.

Total cost of ownership (TCO) of a car is the sum of the annualised fixed (purchasing) costs of the car, variable costs composed of maintenance, repair and tires (MRT), and fuel or electricity costs, for a standard distance driven per year. The purchasing costs of the car consist of the platform, and any applicable combination of ICE, transmission, battery, and electric generator and motor(s).

For a PHEV to be a cost-effective alternative, reductions in fuel consumption and fuel cost must outweigh the added weight and cost of having both a battery and an ICE on board. We do not include country-specific taxes on car purchase, car ownership (road tax) and fuel, but we include 19% VAT, as is common to the EU.

Uncertainty in efficiency and TCO of our selected car configurations is calculated as standard deviation (σ) from the indicated value. We account for uncertainty about electric motor efficiency and transmission efficiency. These lead to uncertainty in fuel consumption and in the minimum battery capacity required to allow 50 or 250 km range. We also account for uncertainty in emissions of fuel production and the cost of batteries and electric motors. We address the uncertainty in specific cost (€ kWh^{-1}) of batteries and the share of km driven on electricity in PHEV through sensitivity analysis. We do not examine uncertainty in driving cycles. We assume no co-variance for propagation of uncertainty in independent conversion steps and full co-variance if the cost uncertainties derive from the same underlying variable.

3. Data

Our dataset for vehicles is not nation specific. However, for country-dependent factors such as electricity demand, electricity generation capacity, and transport demand, we use data for the Netherlands. Where available, we also include data for the entire EU and compare with other countries to widen the validity of our analysis.

3.1. Reference cars and drivetrains

All reference car configurations except the regular diesel car use petrol engines, because the purchase cost of petrol engines is some €1500 lower than of diesel engines [7]. We assume that petrol engine-generators in SHEVs and PHEVs have the same efficiency relative to diesel generators as petrol engines relative to diesel engines in regular cars (see [7]). We also assume a shift from current central motor (CM) drivetrains to wheel motor (WM) drivetrains from 2015 onwards because higher efficiency of wheel motor drivetrains allows for smaller and cheaper engines and battery packs.

For costs of petrol and diesel, we assume an oil price of 80 $ bbl^{-1}, close to the short term projections in the World Energy Outlook 2009 [41]. At this oil price, assuming 41.87 $\text{MJ}_{\text{LHV}}\,\text{kg}^{-1}$ 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 [42,43,7]). This includes 19% value-added tax (VAT) and excise duty [44]. Untaxed, prices are 19.3 € GJ^{-1} or 0.69 € l^{-1} for diesel and 19.9 € GJ^{-1} or 0.64 € l^{-1} for petrol.

We assume that the same electric motors are used to propel SHEVs, PHEVs or BPEVs and electricity consumed per kilometre is therefore the same for both types of cars, as long as the car weight is similar. Based on work by Van Vliet et al. [13], we use an EV drivetrain with a single 74 kW central motor (CM) that consumes 103 ± 20 Wh km^{-1} from 2010 and one with two 29 kW wheel motors (WM) that consumes 89 ± 19 Wh km^{-1} from 2015. In hybrid car configurations, these are powered by a petrol-fuelled engine-generator that produces 53 kWe for a CM drivetrain and 46 kWe for a WM drivetrain with an efficiency of 31%.

TCO is calculated using a 5% social or 10% consumer discount rate, 10 year depreciation period, including VAT but excluding excise duties. For initial TCO calculations we use average annual distance driven in The Netherlands of approximately 14,000 km car^{-1} year^{-1} [45–47].

3.2. Plug-in hybrid and battery powered electric cars

Building on the SHEV drivetrains, we assume PHEVs with an electric range of 50 km and BPEVs with a range of 250 km, again using the methodology and data described in Van Vliet et al. [13].

The efficiency to charge the battery from the grid varies between 89% and 96% in literature, and battery cycle efficiency (combined charge and discharge) varies between 85% and >95% [7,36,48–52]. For EV, we use efficiencies of 90% for charging the battery and 96% for discharging the battery [36]. To account for speed fluctuations that cause some of the electricity from the ICE generator in a SHEV or PHEV (when not driving on grid electricity) to go through the battery, we use a combined efficiency of 97% for transfer of electricity between generator and electric motor (based on [7], as described in [13]).

We use Li-ion batteries with a cost of 960 € kWh^{-1} in 2010, and we assume this reduces to 800 € kWh^{-1} around 2015, and to 400 € kWh^{-1} in the more distant future [53]. These costs are much higher than the minimum target for long term commercialisation of 150 $ kWh^{-1} set by the U.S. Advanced Battery Consortium [54]. The Li-ion batteries we use have a specific energy of 86 Wh kg^{-1}, and we assume this increases to 110 Wh kg^{-1} around 2015 and to 150 Wh kg^{-1} in the more distant future [55,36]. We use a depth of discharge of 70% [13]. We assume a battery pack last for the lifetime of the vehicle, but explore the sensitivity of TCO to a mid-life replacement in Section 5.

Our vehicle platform includes structural reinforcement to support heavy batteries. This increases platform weight by 48 kg compared to a petrol car (based on Ref. [7]). However, advances in specific energy of batteries and the exact reinforcement required can vary [25]. We therefore assume an uncertainty of 50% in total future battery weight including reinforcements.

Increased vehicle weight increases fuel consumption. For cars without regenerative braking, fuel consumption increases by some 3–8% for every 10% increase in car weight [56], due to increased inertial mass and rolling resistance. With regenerative braking, this reduces to approximately 1–5% for every 100 kg increase in car weight [25,36].

To calculate the increase in fuel consumption, we compare the weight of our PHEV and BPEV configurations with that of

Table 1
Projections of the penetration rate of electric vehicles In the EU, US, and Japan in 2030.

Estimate	Region	Institute	Source
9% of sales are PHEVs	OECD	IEA	[57]
21% PHEV and 7% BPEV in 450 ppm scenario	OECD	IEA	[41]
30% of distance by car powered by electricity, mainly in PHEVs (range 5–38%)	EU	ECN	[58]
6% BAU market share of electrical vehicles and 12% in “carbon constraint case”	EU	European Commission	[59]
3% BAU market share of electrical vehicles	EU	European Commission	[60]
Electric vehicles comprise 24% of the light duty vehicle fleet	USA	Berkeley	[61]
2% of light duty vehicles sales is a PHEV	USA	EIA	[62]
20% of distance by car powered by electricity in 2030 and 50% of car sales is a PHEV	USA	EPRI	[63]
Around 27% of the total fleet will consist of PHEVs	USA	U.S. National Renewable Energy Laboratory	[64]
40% of all light duty vehicles will be PHEVs by 2030	USA	Argonne National Laboratories	[64]
PHEVs make up between 10% and 30% of the vehicle fleet	Japan	MIT	[65]
80% of the car fleet consist of PHEVs	Japan	University of Tokyo	[66]

our SHEV configurations (CM to CM, WM to WM) and apply a fuel consumption penalty of $3\pm2\%$ for every 100 kg of extra weight.

3.3. Projections for uptake of electric driving

The amount of electricity used by electric cars depends on the vehicle kilometres travelled in electric cars, which in turn is proportional to the number of PHEVs and BPEVs on the road and, in case of PHEV, the share of electricity in total fuel used. Currently, ICE cars have $\sim$99% market share. Table 1 summarises projections of penetration rates of electric vehicles in 2030 from recent studies.

Two trends emerge from Table 1: PHEVs are projected to be the main electric car type, and the penetration levels do not seem to be very different for different regions. The only exception is a study by the University of Tokyo that forecasts a penetration rate of 80% of PHEV. To assess the impact of different EV penetration levels, two values will be used in our calculations: a low estimate of 6% and a high estimate of 30%.

Total electricity demand for EVs also depends on the number of EVs in use. The number of cars on the road in the Netherlands is projected to rise from 7.2 million cars in 2006–2008 to around 8.1 million in 2015 and around 9 million in 2030 [45,47].

Cars are driven 38 km per day on average in Britain and The Netherlands, and 52 km per day in the USA [46,67–70]. This average is not projected to change significantly [47,71]. We assume this is true for everyday use, and does not include irregular trips (holiday travel by car, etc.). For Britain and The Netherlands, this results in electricity demand of approximately 4.8 kWh day^{-1} per CM EV and 4.0 kWh day^{-1} per WM EV.

The share of trips smaller than 50 km ranges between 60% and 80% [72,73], see also [74,75]. We initially assume that on an annual basis, PHEV are driven 30% on petrol and 70% on electricity (see also [76,77]). We analyse the impact on TCO of different assumptions of annual distances driven and shares of electricity use in PHEVs in Section 4.4.

3.4. Electric vehicle charging

Three different charging setups are currently used in the USA (see Table 2). Type 1 resembles a regular socket dedicated to charging EVs. Type 2 chargers are also available to all residential customers, but require the installation of special equipment [78]. Type 3 are installed at locations where many vehicles need charging quickly, reducing the recharge time to under 10 min. In the EU and Japan, the IEC standard 68851 is in development [79]. This standard allows for normal charging with single phase or three-phase electricity. The equipment is installed in the vehicle and is designed for a maximum load of 40 kW. Fast charging up to 250 kW could become available with fixed chargers.

We use a cost of €480 for the charger, which is included in the car purchase cost [80]. Assessing the cost of different chargers in detail (while charging standards are still in development) is outside the scope of this study.

Table 2 shows that PHEV with a 50 km electric range can easily be charged overnight (19:00–7:00) with any charging equipment. For driving further in BPEV, an IEC68851 or USA type 2 charger should be used to ensure a fully charged car in the morning.

Charging loads add to the existing demand for electricity. Literature suggests a number of charging patterns, as shown in Table 3 [82,32,31].

We examine the uncoordinated and off-peak patterns, as these represent the worst case and best case scenarios. We assume the car is charged in one session per 24-h period. The uncoordinated charging pattern is defined as normal-distributed around 19:30 in the evening with a standard deviation of 3 h. The off-peak pattern depends on the demand pattern, and is defined by fitting a straight demand line between 22:00 and 7:00 so that the total electricity delivered is equal to the total required existing and charging demand.

For consumers, we assume two price levels, depending on the time of day. We use average of household 3-year fixed and variable prices from several large Dutch utilities in spring 2010 (EON Benelux, Electrabel, Eneco, Essent, Nuon, RWE Nederland, see websites). From 7:00 to 23:00, the price is 102 € MWh^{-1}, and

Table 2
Charger types, power per type, vehicle kilometres that can be charged per hour, and hours needed to fully charge an EV battery that provides 50 km range.

Electricity demand household level	Charger type	Power (kW)	2010/central motor		2015/wheel motors	
			km h^{-1}	hours to charge	km h^{-1}	hours to charge
United States	Type l	1.4	12	4.31	14	3.73
52 km day^{-1}	Type 2	3.3	28	1.88	32	1.63
	Type 3	60	502	0.10	581	0.09
European Union	1-Phase	3.5	29	1.30	34	1.12
38 km day^{-1}	3-Phase	10	84	0.45	97	0.39
	Maximum	40	335	0.11	388	0.10

Sources: [81,79,13].

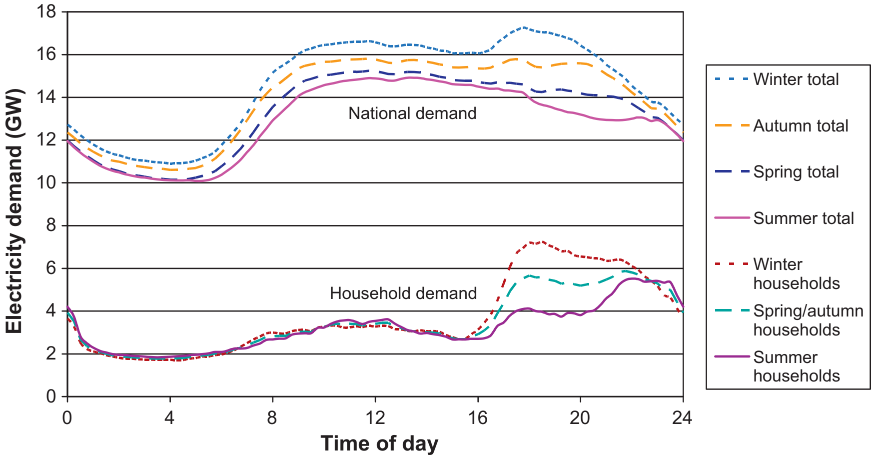

Fig. 1. Average total 2006-2008 national and total 2007 household electricity demand patterns for the Netherlands.

Table 3
Charging scenarios from literature.

Charging pattern	Description
Uncoordinated	EV owners charge their vehicles when they come home until fully charged. No coordination takes place. The peak EV-demand will exacerbate daily peak demand. Both the business as usual and worst case scenario
Delayed	Comparable to the uncoordinated scenario, with the difference that charging starts in the end of the evening. This will shift the peak EV-demand so that it does not coincide with the daily peak demand. Also, charging will be cheaper at the night-rate for electricity
Off-peak	Charging takes place during the night when the overall electricity demand is low and generation is mostly base load. Local utilities can control charging to employ the electricity generation capacity optimally. The advantage for owners is that electricity is cheap during the night
Continuous	Uncoordinated scenario in which vehicle owners charge their vehicles whenever possible. Charging takes place at, for example, home and work throughout the day. Continuous charging results in better charged batteries, which enable more trips to be electricity powered. It also requires an ubiquitous charging infrastructure

from 23:00 to 7:00 the price is 64 € MWh^{-1}. Flat rate prices were 83 € MWh^{-1}, all excluding the 129 € MWh^{-1} Dutch energy tax but including VAT [44].

3.5. Household and overall electricity demand

Electricity demand of a set of 2000 households in an urban environment in the year 2003 is simulated using the SEPATH generator.[1] Since the generator cannot simulate spring and autumn conditions, the average of the summer and winter simulation are used for these seasons. We assume that this demand pattern is representative for all households.

Average household electricity consumption was 3350 kWh year^{-1} in the year 2000 [85]. Based on projections for autonomous increase in this demand ranging between 0.5% and 1.5% per year [85–87,60], we assume an increase of 1.1% per year for households. Consequently, electricity consumption per household is calculated at 3600 in 2007 and 3900 kWh year^{-1} in 2015. We scale the 2003 household pattern from the SEPATH generator to match the total national household electricity demand in 2007 (see Fig. 1), 2010 and 2015.

The total number of Dutch households is projected to rise from 7.19 million households in 2007 to 8.5 million households [88,89]. For sake of simplicity, we assume one car per household.

Fig. 1 also shows the daily pattern of the total Dutch electricity demand per season, based on the average of the years 2006–2008, as obtained from TenneT [90]. Projections for autonomous national electricity demand increases range between 1.1% and 2.4% per year [87,60], and we assume an increase of 1.5% per year.

National demand follows household demand in night and evening, but daytime demand is clearly increased by electricity consumption in the workplace. Both the highest peak demand (winter time evening 17:00 to 20:00) and off-peak (night from 23:00 to 7:00) intervals are caused by dynamics in household demand. However, as demand from households is projected to rise more slowly than overall demand, the influence of households on this pattern will diminish.

3.6. Electricity supply

We use the Dutch vintage electricity generation capacity for our supply calculations. For constructing cost and emission supply curves it is assumed that the electricity generation mix of the Netherlands will not change substantially in the near future. Plans for new power plants support this, as well as the intentions of the Dutch government. Furthermore, the 20–60 year lifespan of power plants makes the generation mix rather static [91–93].

Table 4 shows existing and projected vintage electricity generation capacity, taken from Van den Broek et al. [94]. For 2015, this assumes three currently planned pulverised coal-fired power plants with a total capacity of 3.4 GW and several NGCC plants with a total capacity of 5.9 GW are built.

Merit order is based on variable operating and maintenance (O&M) and fuel costs, except for nuclear, wind, PV and CHP (except gas engine CHP), which are always used when available. We do not take a CO_2 price into account when determining the merit order.

For 2030, only the plants that remain from the 2015 vintage are included, to show the inertia in the composition of the generation capacity. New capacity will be needed to meet demand after 2015, but projections regarding the type of plants built after 2015 are beyond the scope of this chapter. If GHG emissions from electricity generation are to be reduced, we can expect an increasing role for electricity generation using renewable resources like

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[1] SEPATH <fn0005>is a fully validated pattern generator that simulates the present day electricity demand of households over a 24-hour period. It was developed by KEMA and IVAM [83,84].

Table 4
Electricity generation capacity in the Netherlands in 2005, 2010, 2015 and remaining 2015 vintage in 2030, in order of merit.

Vintage capacity	CO_2 emissions (tonne MWh^{-1})	Variable costs (€ MWh^{-1})	Capacity factor	Generation capacity installed			
Technology merit order				2005	2010	2015	2030
Preferred capacity[a]	Mixed, not relevant		Included	3858	3910	3621	1217
PC super critical new	0.85	16	0.89	0	0	3600	3600
PC super critical	0.89	16	0.89	1230	1230	1230	1230
PC sub critical	1.00	18	0.89	2690	2690	2690	2045
Integrated coal gasification	1.03	19	0.87	253	253	253	253
NGCC new	0.43	62	0.89	0	2098	5869	5869
NGCC	0.48	69	0.89	4809	3782	3718	2961
Gas-fired power plant	0.61	88	0.80	4527	4068	2643	0
CHP gas engine	0.61	89	0.46	1794	2517	1810	0
Gas turbine peaking plant	0.70	103	0.25	239	0	0	0

Source: [94].

[a] Preferred capacity in the merit order consists of nuclear power, gas turbine district heating, PV, onshore and offshore wind, and most varieties of CHP. *Abbreviations*: PC: pulverised coal-fired; NGCC: natural gas combined cycle; CHP: combined heat and power.

Table 5
Battery capacity, battery weight, total car weight, range (+o) on full battery, and TTW electricity consumption (including correction for weight) of EV configurations investigated in this study.

Vehicle configuration	Battery (kWh)	Battery weight (kg)	Car weight (kg)	Range on full battery (km)	Electricity consumption (Wh km^{-1})
SHEVCM 2010	1.1	10	1310 ± 20	8 ± 1	Petrol only
SHEVWM future	1.5	10 ± 0	1220 ± 0	11 ± 2	Petrol only
PHEV CM 2010	7.4	80 ± 20	1380 ± 20	50 ± 7	122 ± 27
PHEVWM future	6.4	40 ± 20	1250 ± 20	50 ± 7	104 ± 23
BPEVCM 2010	36.9	410 ± 80	1530 ± 80	250 ± 34	127 ± 35
BPEVCM 2015	36.9	340 ± 180	1450 ± 180	250 ± 34	124 ± 32
BPEVWM 2015	31.8	290 ± 160	1350 ± 160	250 ± 37	107 ± 29
BPEVWM future	31.8	210 ± 120	1270 ± 120	250 ± 37	104 ± 25

biomass and wind, and for the use of carbon capture and storage (c.f. [95,96]).

From 2000 to 2009, grid losses have accounted for 3.8% of electricity produced in the Netherlands [97]. The Dutch grid is relatively efficient, compared to the whole EU where losses were reduced from 8.7% in 1996 to 7.2% in 2007 [98]. We adjusted variable costs and GHG emissions of delivered electricity and available electricity for losses in the Dutch grid. We include the difference between Dutch and EU grids in our uncertainty calculations.

As we assume no additional capacity is built for charging EV, there are no additional capital costs. The costs for charging EV at a specific hour in a year are determined by the variable O&M and fuel costs of the marginal available generation plants.

To calculate emissions and variable costs, we use emissions factors from JRC and price projections from the World Energy Outlook 2009 [7,41]. For coal, emissions are 108.4 kg $CO_{2\,eq}$ GJ^{-1}, including emissions from mining and transport, and price is 1.8 € GJ^{-1} around 2010 and 2.0 € GJ^{-1} in 2015. For natural gas, emissions are 69.5 kg $CO_{2\,eq}$ GJ^{-1}, including recovery and 4000 km pipeline transport, and price is 9.2 € GJ^{-1} around 2010 and 10 € GJ^{-1} in 2015.

4. Results

4.1. Plug-in hybrid and battery powered car configurations

Table 5 shows the battery-related aspects of our SHEV and EV configurations. The increase in fuel consumption due to weight (3 ± 2% per 100 kg extra weight) ranges up to 14% compared to reference SHEV. Table 6 shows component costs and total purchasing costs of our reference cars, SHEV and EV configurations.

Table 7 shows GHG emissions of our car configurations, using petrol, diesel and electricity produced by wind or PC sub-critical power plants. Fig. 2 shows GHG emissions from electric driving in 2015 PHEV with CM and WM configurations using fossil fuels, calculated from drivetrain electricity consumption, conversion efficiency of petrol and power plants, grid losses, and relevant emission factors. GHG emissions from using fossil fuels to charge CM EV range roughly between 127 g $CO_{2\,eq}$ km^{-1} using electricity from a sub-critical coal plant to 55 g $CO_{2\,eq}$ km^{-1} using a natural gas combined cycle plant. Emissions using improved coal plants, petroleum-power plants and less efficient natural gas plants fall within this range.

Table 6
Component costs and total car purchasing cost of car configurations investigated in this study.

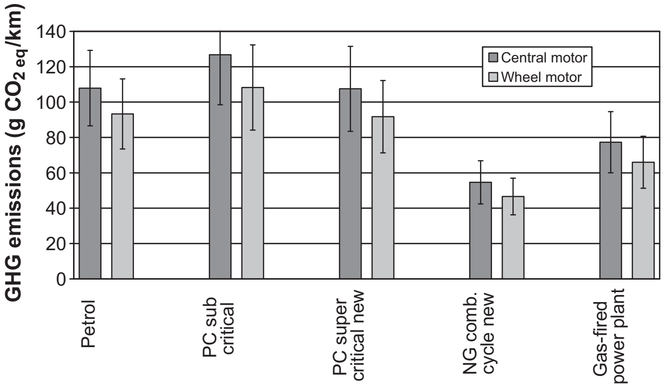
Vehicle configuration	Platform	Electrical drive	ICE/generator	Battery	Total (€)
Regular diesel	15,730	0	5640	0	21360
Regular petrol	15,440	0	3730	0	19160
Parallel hybrid	15,440	3660	2980	2830 ± 0[a]	24910 ± 0
SHEVCM 2010	15,730	4380 ± 750	3020 ± 210	1740	24860 ± 780
SHEVWM future	15,730	2330 ± 720	2730 ± 190	580	21370 ± 750
PHEV CM 2010	15,730	4380 ± 750	3020 ± 210	7550 ± 1370	30670 ± 1580
PHEVWM future	15,730	2330 ± 720	2730 ± 190	3030 ± 540	23820 ± 920
BPEVCM 2010	15,730	4380 ± 750	0	35800 ± 6870	55900 ± 6910
BPEVCM 2015	15,730	4380 ± 750	0	29970 ± 5730	50070 ± 5780
BPEVWM 2015	15,730	2330 ± 720	0	25960 ± 5390	44020 ± 5440
BPEVWM future	15,730	2330 ± 720	0	13220 ± 2690	31280 ± 2790

[a] The parallel hybrid car has a 2.9 kWh battery.

Table 7
WTT, tank-to-wheel (TTW) and total WTW emissions from reference drivetrains in gram $CO_{2\,eq}$ km^{-1}.

Vehicle configuration	Fuel	WTT emissions ($g\,km^{-1}$)	TTW emissions ($g\,km^{-1}$)	Total emissions ($g\,km^{-1}$)
Regular diesel	Diesel	25 ± 5	131	156 ± 5
Regular petrol	Petrol	22 ± 6	140	163 ± 6
Parallel hybrid	Petrol	18 ± 4	112	129 ± 4
SHEV central motor	Petrol	15 ± 4	93 ± 18	108 ± 21
SHEV wheel motor	Petrol	13 ± 4	81 ± 17	93 ± 20
PHEV CM 2010	Electricity/petrol[a]	3–116	29 ± 6	25–151
PHEVWM future	Electricity/petrol[a]	2–99	24 ± 5	22–129
BPEVCM 2010	Electricity	0–166	0	0–166
BPEVCM 2015	Electricity	0–163	0	0–163
BPEVWM 2015	Electricity	0–139	0	0–139
BPEVWM future	Electricity	0–136	0	0–136

[a] PHEV emissions use 70% electricity and 30% petrol.



Note: PC: Pulverised coal, NG: natural gas.

Fig. 2. GHG emissions from driving (g $CO_{2\,eq}$ km^{-1}) on petrol and on electricity from fossil energy resources in CM and WM 2015 PHEV configurations. *Note*: PC: Pulverised coal, NG: natural gas.

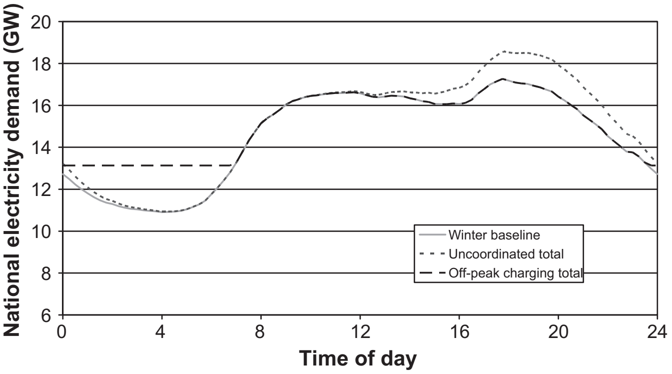


Fig. 3. Electricity demand pattern in winter at national level with and without CM 2015 BPEV in 2015 at 30% penetration.

We find that EVs charged using electricity from coal do not have significantly different GHG emissions from driving in regular cars. WM EV charged with electricity from NG may reduce emissions to as low as 47 $g\,km^{-1}$. These emissions results are similar to those found by other authors (e.g. [31], relative emissions pattern based on USA vehicles repeated in Refs. [48,36]).

The variation in GHG emissions of electric driving is considerable, and depends more than anything else on the mix of electricity sources used for charging. GHG emissions from electricity from a modern coal-fired power plant cause emissions that are approximately equal to those when driving the same PHEV on petrol.

4.2. Additional electricity demand from cars

Matching supply to demand, electricity generation capacity in the Netherlands in 2010 is sufficient to allow for uncontrolled charging with 6% penetration of EV. Projected generation capacity for 2015 is sufficient for uncontrolled charging up to 30% penetration of EV.

At a national level in the Netherlands in 2015 using a CM 2015 BPEV, we project EV charging to increase total demand by 3% at a 30% penetration rate of EV, as shown in Table 8. However, the charging scenario makes a strong difference: Uncoordinated, the minimum load does not change but peak load increases by 7%. No additional peak load occurs if a wheel motor drivetrain used. With off-peak charging, the minimum load increases by 20% but the peak does not increase at all, resulting in an increased and more stable base load, and no need for additional investment for driving. Fig. 3 shows the resulting demand patterns on a national level.

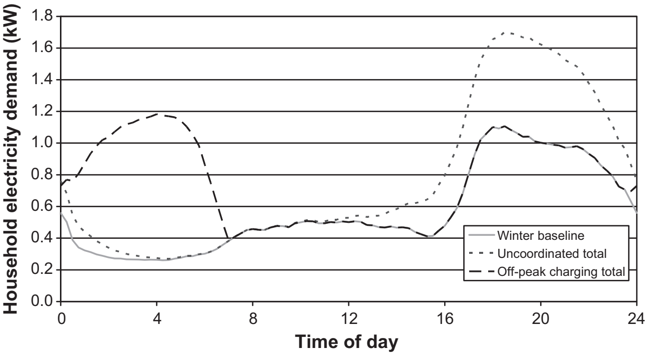


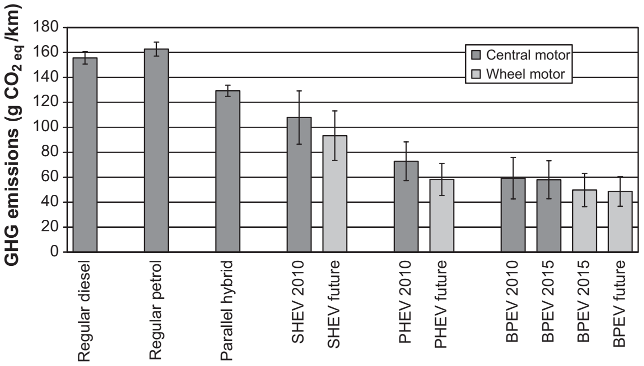
Fig. 4. Electricity demand pattern in winter at household level with and without CM 2015 BPEV in 2015 at 30% penetration.

Table 8
Electricity demand without (baseline) and with (uncoordinated and off-peak) electric driving at 30% penetration rate of CM 2015 BPEV.

Daily demand	National level, 8.1 million cars			Household, single car		
Winter 2015	Total ($GWh\,day^{-1}$)	Maximum (GW)	Minimum (GW)	Total ($kWh\,day^{-1}$)	Maximum (kW)	Minimum (kW)
Baseline	351	17.3	10.9	14	1.11	0.26
Uncoordinated	362	18.6	10.9	18	1.70	0.27
Off-peak	362	17.3	13.1	18	1.18	0.38

Table 9
Average costs, including VAT and excluding excise duty, and emissions of additional electricity for electric driving at 30% penetration of CM 2015 BPEV.

Additional electricity	National level, 8.1 million cars			Household, single car	
Winter 2015	Generation cost		Emissions	electricity price	
	€ MWh^{-1}	€ km^{-1}	g CO$_2$ km^{-1}	€ MWh^{-1}	€ km^{-1}
6% Penetration					
Uncoordinated	70	0.009	62	97	0.012
Off-peak	65	0.008	57	64	0.008
30% Penetration					
Uncoordinated	71	0.009	62	97	0.012
Off-peak	65	0.008	57	64	0.008



Note: Emissions for PHEV use 70% electricity and 30% petrol.

Fig. 5. GHG emissions from driving (g CO$_{2\text{ eq}}$ km^{-1}) car configurations investigated in this study. Note: Emissions for PHEV use 70% electricity and 30% petrol.

Fig. 4 shows the resulting demand patterns on a household level. This pattern is even more pronounced at household level, where additional demand would be 35%, but peak increase for uncoordinated charging would be 54% and base load increase for coordinated charging would be 47%. The peak increase for household demand using coordinated charging would be around 7%. Though the increased peak demand from uncontrolled charging is nationally within projected 2015 peak generation capacity, the increase in peak household demand indicates that distribution infrastructure may locally need strengthening if the penetration rate of EV becomes significant. Further research into the effects of EV charging on local (district or street level) infrastructure may therefore be needed.

EV charging patterns have most impact when household demand is highest or lowest. Therefore, despite households' minority share in total demand, household demand dynamics are most relevant in determining the impact of EV on national electricity demand.

The impact of off-peak charging is different on household level than on national level, to a point where night-time demand is almost equal to peak demand without EV charging. However, as long as night/off-peak electricity prices remain significantly lower than afternoon/evening prices, this should not affect the incentive to charge off-peak.

4.3. GHG emissions and costs of EV charging

Table 9 shows the cost and emissions of additional electricity required for driving a PHEV or BPEV. There is no significant difference in the average cost or emissions for different levels of penetration. GHG emissions reflect that most of the electricity used for charging is generated with efficient natural gas-fired power plants (NGCC). Both without EV charging and with off-peak charging, we project that NGCC is the *de facto* marginal source at all times in all seasons in the Netherlands in 2015.

The off-peak charging pattern results in a 8% reduction in GHG emissions and 34% reduction in EV charging price at a household level compared to uncoordinated charging (excluding possible excise duties on electricity). Emissions are higher in case of uncoordinated charging because less efficient NG power plants used to supply electricity for charging. Including uncertainties in electricity consumption and variation between CM and WM cars, GHG emissions are 35–77 g km^{-1} when charging from the Dutch grid in 2015. This is a reduction of 51–78% compared to regular cars and by 17–73% compared to other hybrids.

Fig. 5 shows the total GHG emissions per km for our reference cars, SHEV and EV. It shows that PHEV can achieve the lion's share of the GHG reductions that are possible with EV. GHG emissions may be reduced further by reducing the CO$_2$ intensity of liquid fuels and electricity.

Using the electricity costs from Table 9, we arrive at the variable cost of driving shown in Table 10:

Electricity costs a third of diesel or petrol per km, but the variable costs are still largely determined by maintenance, repair and tires (MRT). The variability introduced by charging patterns is 8–9%.

4.4. Total cost of EV ownership

Table 11 shows the TCO of PHEV and BPEV. TCO is dominated by purchasing cost of the vehicle, rendering the effect of fuel costs and charging patterns negligible. Fig. 6 compares TCO of reference cars, SHEV, PHEV and BPEV.

BPEV are at least 800 € year^{-1} more expensive than the reference cars or any of the alternatives, even at a battery cost of €400 kWh^{-1}. By contrast, the future wheel motor PHEV is not more expensive than any alternative but the current regular petrol car and the future WM SHEV.

Table 10
Variable cost of CM electric driving (€ km^{-1}) at 30% penetration in winter using off-peak charging.

Vehicle configuration	MRT	Petrol	Electricity (grid)	Total (€ km^{-1})
PHEV central motor	0.043	0.029 ± 0.007	0.008 ± 0.003	0.057 ± 0.004
PHEV wheel motor	0.043	0.025 ± 0.006	0.007 ± 0.002	0.055 ± 0.003
BPEV central motor	0.043		0.008 ± 0.003	0.049 ± 0.003
BPEV wheel motor	0.043		0.007 ± 0.002	0.048 ± 0.002

Note: Total variable costs for PHEV use 70% electricity and 30% petrol.

Table 11
Total cost of ownership (TCO, € year^{-1}) breakdown for car configurations investigated in this study using a 5% social discount rate, VAT only, driving 14,000 km year^{-1} and depreciating over 10 years.

Vehicle configuration	Annualised purchase	MRT	Diesel/petrol	Electricity	TCO (£ year^{-1}, VAT only)
Regular diesel	2770	610	570	0	3940
Regular petrol	2480	570	630	0	3690
Parallel hybrid	3230 ± 0	570	500	0	4300 ± 0
SHEVCM 2010	3220 ± 100	610	400 ± 80	0	4230 ± 130
SHEVWM future	2770 ± 100	610	350 ± 70	0	3720 ± 120
PHEV CM 2010	3970 ± 200	610	120 ± 30	80 ± 24	4780 ± 210
PHEVWM future	3090 ± 120	610	110 ± 20	60 ± 21	3860 ± 130
BPEV CM 2010	7240 ± 890	610	0	110 ± 41	7960 ± 900
BPEV CM 2015	6480 ± 750	610	0	110 ± 38	7200 ± 750
BPEVWM 2015	5700 ± 700	610	0	100 ± 34	6400 ± 700
BPEV WM future	4050 ± 360	610	0	90 ± 31	4750 ± 360

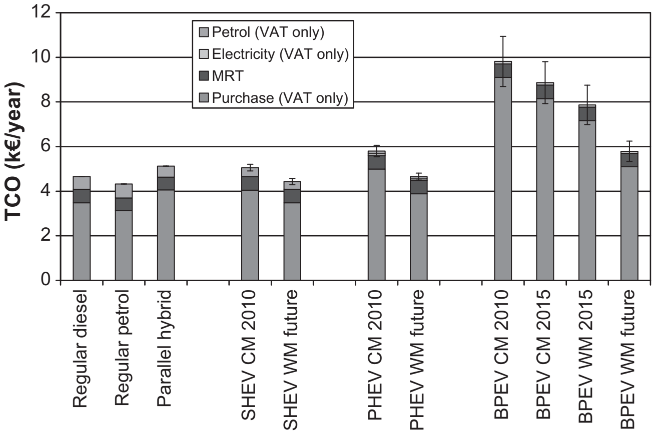


Fig. 6. Total cost of ownership (TCO, k€ year^{-1}) breakdown of our car configurations using a 10% consumer discount rate and VAT only, driving 14 000 km year^{-1} and depreciating over 10 years.

However, PHEV TCO in Table 11 depends on driving on 70% electricity and on the relative impact of variable costs. We therefore examine the sensitivity of TCO comparisons to driving distance and share of electrically fuelled km driven (assuming that these shares are feasible).

When we plot the TCO for different configurations as a function of driving distance and feasible share of electrically fuelled km driven, 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. 7 shows the isopleths curves for our PHEV and BPEV configurations and reference cars.

Fig. 7 shows that low share of electric driving reduces competitiveness of PHEV, but that a motorist who drives long distances (e.g. 40,000 km per year) with access to recharging away from home may still benefit from a future PHEV.

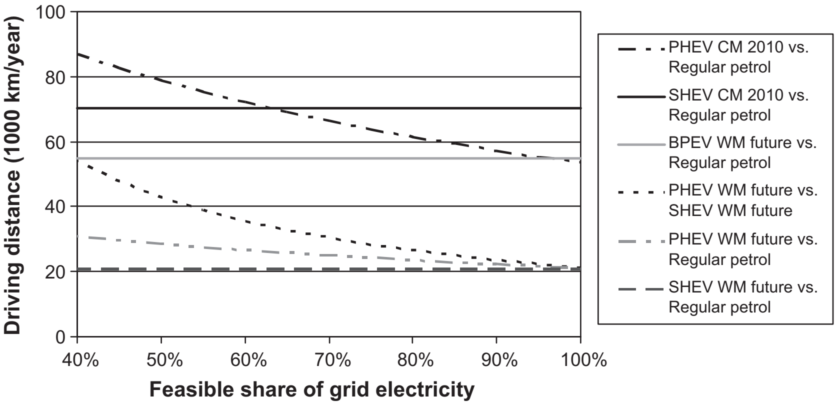
Increasing the oil price from 80 $ bbl^{-1} to 120 $ bbl^{-1} does not change the relative positions of the lines in Fig. 7, but reduces the driving distance for all isopleths by one-third. For example, at 120 $ bbl^{-1}, current CM SHEV have lower TCO than regular petrol cars at a driving distance of more than 54,000 km year^{-1}. TCO cost for SHEV are increased by approximately 100 € year^{-1} compared to Table 11.

Using results from Tables 7, 9 and 11 we calculate the approximate GHG abatement costs for our car configurations, as shown in Fig. 8. Results indicate the future SHEV and PHEV may be competitive with other options for GHG emissions reductions, but current EV technology and BPEV are not.

5. Discussion

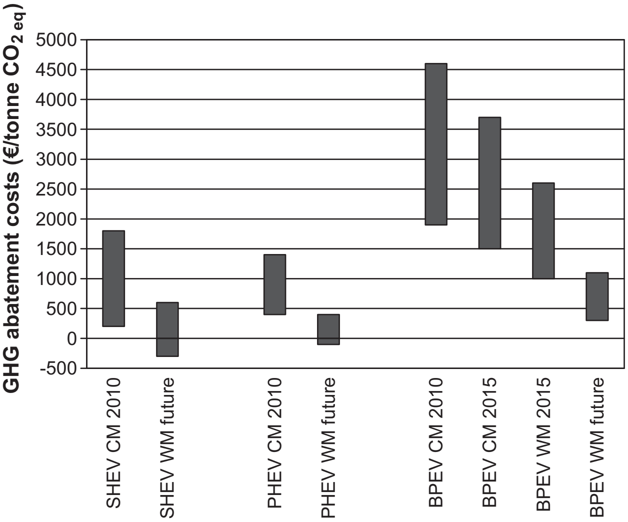
5.1. Effect on electricity generation infrastructure

Electric driving is potentially an extra source of revenue for utilities. If charging is done off-peak, a 30% penetration rate causes an increase of 3% in total electricity demand. This can be met without additional investments in electricity generation plants. Electrification of the entire car fleet would result in an increase of around 10% in total electricity demand, which can still be met with existing generation capacity, without higher peak loads at a national level and with 7% higher peak loads at the household and district level using a CM EV or no higher peak load using a WM EV.



Note: For every line, the configuration listed first in the legend has lowest cost above the isopleth line, and the configuration listed second has lowest cost below the line.

Fig. 7. Lowest TCO isopleths for SHEV, PHEV, BPEV and reference cars, using VAT only and a 10% consumer discount rate. Note: For every line, the configuration listed first in the legend has lowest cost above the isopleth line, and the configuration listed second has lowest cost below the line.



Note: Range in abatement costs is caused by uncertainty in EV costs, GHG emissions and by comparing to both petrol and diesel cars.

Fig. 8. GHG abatement costs (€ $tonne^{-1}$ CO_2 equivalent) for EV configurations investigated in this study compared to regular diesel and petrol cars, in the Dutch electricity supply context, using a 5% social discount rate and VAT only, driving 14,000 km $year^{-1}$ and depreciating over 10 years. Note: Range in abatement costs is caused by uncertainty in EV costs, GHG emissions and by comparing to both petrol and diesel cars.

However, if EV charging is uncoordinated and there are no incentives to charge off-peak, the peak load would increase substantially, as described in Section 4.2. This increase of peak load is much more pronounced on the household level than on the national level (compare Figs. 3 and 4). Furthermore, there is not much incentive (other than lower off-peak rates) to adopt coordinated charging on the household level, because the impact of charging patterns on total household costs is relatively small, while this incentive is much stronger for utilities and grid operators. Consequently, if EVs will be concentrated in certain districts or even streets, uncoordinated charging may quickly cause the local distribution grid to be overloaded.

The household demand pattern resulting from off-peak charging (see Fig. 4) has implications for CHP installations, as the combined pattern resembles that of household heat demand in a country like the Netherlands (see [99]). District and micro-CHP would become more viable with increased penetration of electric vehicles. We therefore recommend further investigation of combining CHP with EV charging.

The longevity of the existing generation capacity precludes rapid changes in the GHG emissions profile of EV. In the Dutch context, 68% of 2015 capacity is projected to still be in use in 2030 (see Table 4). In the medium term, GHG emissions from EV driving are relatively fixed. There is therefore neither a risk of EV electricity being entirely supplied from coal, nor a possibility to supply all of it from renewables.

This limits the GHG emissions reductions that may be achieved through EV. However, the emissions profile may change, for example, if stringent GHG reduction policies cause existing electricity generation capacity to be retired early or retrofitted for co-firing of biomass and/or carbon capture and storage (see also [96]). Alternatively, complementary means of reducing transport emissions may be used, such as sustainable biofuels.

5.2. Uncertainty in energy use

Table 5 shows that the weight increase for future WM vehicle configurations is less than 5% compared to the reference cars (as in Ref. [13]). However, central motor PHEV and BPEV shows up to 17% increase weight, leading to significantly increased electricity consumption. This increase would be even more significant in larger size cars (mid-size sedans up to SUV) and in case battery-powered range were increased beyond 50 km for PHEV and 250 km for BPEV. Significant uncertainties exist in the GHG emissions from electric driving, which depend to a large extent on energy efficiency of the drivetrain (in addition to electricity source). We arrive at an uncertainty in emissions of around 22%.

However, additional minor uncertainties could arise from variability in charger efficiency and battery cycle efficiency. In the context of current Dutch electricity generation capacity in the short term, any additional electricity is likely to be generated from natural gas, and therefore does not significantly alter the overall GHG emissions profile. However, GHG emissions would rise more in supply contexts where the marginal electricity source causes high emissions.

Driving patterns (as represented in drive cycles) have a major impact on fuel consumption and affect electric drivetrains differently than ICE drivetrains. Further research, using comparable vehicle platforms, may shed light on the exact impact of driving patterns.

5.3. Battery costs

Our calculations assume EV batteries last the entire lifetime of the EV. At present Li-ion batteries have a calendar life of around 5 years, which suggests that one mid-life replacement may be necessary [100]. In parallel hybrids at least, cycle life has not proven to be problematic, as batteries in hybrid taxis are reported to have lasted over 350,000 km [101]. If a mid-life battery replacement is needed, discounted TCO of PHEV increase by 1640–1940 € $year^{-1}$ or 33–35% compared to the results in Table 11. TCO increase for BPEV would be 60–94%. This reinforces our conclusion that BPEV are currently economically uncompetitive.

As batteries entirely account for additional weight and cost between SHEV and our PHEV and BPEV configurations, we expect some motorists may favour PHEV configurations with a battery-powered range between 20 and 50 km, or BPEV configurations with ranges between 100 and 250 km. Lower cost and weight may outweigh concerns over range for some. The PHEV is more flexible in this sense, because it also carries an ICE and the battery size determines the share of km driven on electricity, rather than restrict driving range.

We calculate that TCO of a future WM BPEV configuration with 100 km electric range is roughly equal to that of regular and hybrid cars, but less advanced BPEV configurations remain more expensive. PHEV with 20 km electric range have approximately equal cost to SHEV. Future BPEV also become competitive if cost of batteries can be reduced to 150 € kWh^{-1}, but this implies an 85% reduction in cost compared to current batteries.

The battery cost reductions we use are based on policy targets and not on a comprehensive analysis of battery technology. Prices of batteries have dropped faster than expected in recent years [102]. However, due to fierce competition doubt have arisen over the quality and expected life span of these reduced cost batteries [102]. As replacing the batteries early would lead to much higher TOC, we use conservative estimates for battery costs that also include aggregation of battery cells into vehicle-ready packs. It therefore remains uncertain if the reduction of battery costs to 150 € kWh^{-1} can be reached at all, and if the lesser reduction to 400 € kWh^{-1} can be reached without compromising on quality and longevity, especially in 2015. More research is needed to assess future battery costs.

5.4. Generalising our findings

As lifestyles, working hours and household technology are fairly similar across industrialised nations and households, demand patterns without EV charging should be fairly consistent, except for higher use of air conditioners in the daytime in warmer climates. We therefore expect our findings on the impact of charging patterns on demand to be applicable to industrialised countries.

Conversely, our results for marginal supply and emissions are based on the Dutch supply and demand. Generation capacity varies strongly between countries, with wide ranges in the use of coal, nuclear, hydro and natural gas. Our calculation for cost of charging and GHG emissions are therefore circumstantial. More generally, increased base load due to electric driving could lead to increased use of coal-fired electricity with high GHG emissions. However, unless a majority of a country's electricity generation capacity will reach the end of its lifespan in the next decade, GHG emissions profiles of EV may to remain close to current values.

Our TCO calculations use technology assumptions that are not nation-specific. Our finding that charging patterns have negligible impact on TCO is widely applicable. However, we assume no specific tax context, whereas taxation can strongly influence the relative TCO of car alternatives. For example, the Dutch tax context is advantageous to PHEV and BPEV configurations as EV buyers are currently exempt from a 45% purchasing tax, pay half of the annual road tax and pay lower fuel taxes because of lower fuel consumption (see [13]).

6. Summary and conclusions

We examined efficiency and costs of current and future EV, as well as the impact from charging EV on electricity demand and infrastructure for generation and distribution, and thereby on GHG emissions.

Uncoordinated charging would increase national peak load by 7% at 30% penetration rate of EV and household peak load by 54%, which may exceed the capacity of existing electricity distribution infrastructure. At 30% penetration of EV, off-peak charging would result in a 20% higher, more stable base load and no additional peak load at the national level and up to 7% higher peak load at the household level. Therefore, if off-peak charging is successfully introduced, electric driving need not require additional generation capacity, even in case of 100% switch to electric vehicles.

WTW GHG emissions from electric driving depend most on the fuel type (coal or natural gas) used in the generation of electricity for charging, and range between $0\,\mathrm{g\,km^{-1}}$ (using renewables) and $155\,\mathrm{g\,km^{-1}}$ (using electricity from an old coal-based plant). Based on the generation capacity projected for the Netherlands in 2015, additional electricity for EV charging would largely be generated using natural gas, emitting $35–77\,\mathrm{g\,CO_{2\,eq}\,km^{-1}}$. In the Dutch context, emissions vary little with charging patterns, and are unlikely to change much before 2030.

Emissions from EV charging are lower than emissions from regular or parallel hybrid cars, and equal to emissions from SHEV if electricity were generated from modern coal-fired plants.

We find that TCO of current EV are uncompetitive with regular cars and series hybrid cars by more than $800\,€\,\mathrm{year^{-1}}$. TCO of future wheel motor PHEV may become competitive when batteries cost $400\,€\,\mathrm{kWh^{-1}}$, even without tax incentives, as long as one battery pack can last for the lifespan of the vehicle. However, TCO of future BPEV is at least 25% higher than of SHEV or regular cars. This cost gap can be overcome if the cost of batteries drops to around $150\,€\,\mathrm{kWh^{-1}}$ in the future. Variations in driving cost from charging patterns have negligible influence on TCO.

GHG abatement costs using PHEV are currently $400–1400\,€\,\mathrm{tonne^{-1}\,CO_{2\,eq}}$ and may come down to -100 to $300\,€\,\mathrm{tonne^{-1}}$. Abatement cost using BPEV are currently above $1900\,€\,\mathrm{tonne^{-1}}$ and are not projected to drop below $300–800\,€\,\mathrm{tonne^{-1}}$.

We find that EV can be integrated into the Dutch grid with few additional investments apart from coordinated chargers. Using PHEV, this need not increase the cost of driving significantly and could reduce emissions from driving by more than 70% compared to diesel and petrol cars and by more than 55% compared to other hybrids that use petrol. We therefore recommend further development of electric drivetrains and batteries for use in SHEV and PHEV.

With respect to the possible future deployment of EV, we recommend further research into combining CHP with EV charging, effects of EV charging on local electricity distribution grids, cost developments of batteries and chargers, and the effect of driving patterns and different vehicle classes on EV fuel consumption. We also recommend integrating WTW analysis with analysis of energy and GHG emissions from EV manufacturing, as well as impacts of EV on non-GHG emissions, and investigating the possible role of EV in conjunction with other car alternatives, low or zero carbon fuels and green electricity in reducing GHG emissions.

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