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Title: Plug-in hybrid electric vehicles - a low-carbon solution for Ireland?

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Abstract:

Between 1990 and 2006, the primary energy requirement of the Irish transport sector increased by 166%. Associated greenhouse gas (GHG) emissions have followed a corresponding trajectory, and are responsible – at least in part – for Ireland’s probable failure to meet its Kyoto targets. As in most countries, Ireland’s transport sector is almost totally reliant on oil – a commodity for which Ireland is totally dependent on imports – and therefore vulnerable to supply and price shocks. Conversely, the efficiency and Carbon intensity of the Irish electricity supply system have both improved dramatically over the same period, with significant further improvements projected over the coming decade. This paper analyses the prospects for leveraging these changes by increasing the electrification of the Irish transport sector. Specifically, the potential benefits of plug-in hybrid-electric vehicles (PHEV) are assessed, in terms of reducing Primary Energy Requirement (PER) and CO<sub>2</sub> emissions. It is shown that, on a per-km basis, PHEV offer the potential for reductions of 50% or more in passenger car PER and CO<sub>2</sub> intensity. However, the time required to turn over the existing fleet means that a decade or more will be required to significantly impact PER and emissions of the PC fleet.

Keywords: plug-in, hybrid, transport, energy, CO<sub>2</sub>, PHEV

Main text

The Irish transport sector

The transport sector is responsible for a significant fraction of Ireland's total primary energy requirement (TPER): in 2006 it accounted for 34% (5,487 ktoe) of TPER, or 41% (5,393 ktoe) of final energy demand, consuming more than twice as much as industry (Howley et al, 2007a). The growth rate of the energy requirement has also been impressive: between 1990 and 2006, transport sector PER increased by 167%, the fastest growth rate of all sectors during that period (ibid). This upsurge coincides with an unprecedented period of economic growth in Ireland (Central Statistics Office 2003 and 2008a; UNECE 2008) – the so-called Celtic Tiger phenomenon – and a contemporaneous rise in population of over 20% (UNECE 2008). This combination of factors yielded an increase in private car ownership per 1,000 adults of 69% between 1990 and 2006 (Howley et al, 2007a), which, coupled with a move towards larger engine sizes and reliance on private cars for commuting to and from work, is widely believed (e.g. EPA 2008a and 2008c, Department of Transport 2008a) to be responsible for much of the surge in transport energy requirement.

Greenhouse gas (GHG) emissions from the Irish transport sector have followed a corresponding trajectory; data from the Irish Environmental Protection Agency show an increase of 165% between 1990 and 2006 (EPA 2008c), a proportional increase five times greater than for any other sector. Consequently, transport's share of Irish GHG emissions increased from 9% in 1990, to 20% in 2006. Provisional data for 2007 indicates a continuation of this trend, with transport sector emissions increasing by a further 4.75% (649.6 kt CO<sub>2eq</sub>), and sectoral share increasing to almost 21% of the national total (EPA 2008c). This continued growth in transport sector emissions means that, despite a trend towards reduced GHG emissions from the energy (primarily electricity generation) sector in particular, it is unlikely that Ireland will meet its Kyoto targets without purchasing carbon credits (EPA 2008c).

As in most countries, Ireland's transport sector is almost totally reliant on oil; in 2006 this reliance exceeded 99% (Howley et al, 2007a). Having no indigenous oil resource, Ireland is totally dependent on imports, and therefore vulnerable to supply and price shocks. Indeed, Ireland's import dependence for all forms of energy exceeded 90% in 2007, making her the third most dependent amongst EU-27 member states, behind Cyprus (102.9%) and Luxembourg (98.9%) (European Commission DG TREN, 2008). This contrasts with the situation in 1990, when import dependence was approximately 68% (O'Leary et al., 2007a), and with the average import dependency for energy of the EU27 at 53.8% (European Commission DG TREN, 2008). The increased import dependence is due in part to the decline in indigenous natural gas production from Kinsale since 1995, and decreasing peat production (Howley et al 2007b); however, the strong increase in oil imports required to satisfy transport sector growth has also been a major factor.

It is evident, therefore, that the continued oil-dependence of the Irish transport sector has significant negative implications in terms of TPER, GHG emissions, and import dependence. On the other hand, personal transport is central to individual freedom, to economic development, and as noted by then Irish Minister for Communications, Marine and Natural Resources in 2005 "...central to family life. Central to careers. Central to commerce, entertainment – and health. It's one of those rare factors which reaches into every aspect of our existence." (Dempsey, 2005).

The challenge lies in resolving this conflict; the potential solution addressed in this paper entails the increased electrification of the Irish transport sector.

The Irish electricity system

As might be expected (given the high level of economic and population growth from 1990-2006) Irish electricity consumption increased significantly over the period, from 11.9 TWh

to 25.9 TWh – an increase of 118% (Howley et al 2007b). However, in contrast with the transport sector, primary energy requirement (PER) and CO<sub>2</sub> emissions associated with electricity generation increased much more slowly, by 68% (Howley et al, 2007b) and 32% (author's calculations), respectively. The improved performance of the electricity sector was due to a number of factors, principal amongst them being the introduction of high-efficiency combined-cycle gas turbine (CCGT) generating plant, the phasing out of older, oil- and peat-burning generation plant, and consequently increased penetration of natural gas in the generation fuel mix. Since 1999 the growth rate of wind-generated electricity has also been high, averaging 34% per annum over the period, admittedly from a very low base (Howley et al, 2007b). As a result, wind-generated electricity accounted for 5.6% of gross electricity consumption in 2006 (Howley et al, 2007c). Significantly, the high levels of growth in wind generation are expected to continue well into the next decade, as discussed below. The net effect of these changes to date has been to improve the efficiency of electricity supply – at the wall socket – from 33% in 1990 to 40.6% in 2005 (Howley et al, 2007c), and to reduce the carbon intensity from over 925 g.kWh<sup>-1</sup> in 1990 to just 601 g.kWh<sup>-1</sup> in 2006 (Howley et al, 2007 b).

The import-dependency of electricity generation is lower than that of the transport sector, but still relatively high at about 83% in 2006 (author's calculation based on Howley et al, 2007b). Import dependence has increased significantly from the 1990 value of about 50%, primarily due to the decline in output from the indigenous Kinsale gas field over that period. Looking forward, however, the Corrib gas field is expected to enter production around 2010, and will satisfy between 10% and 30% of projected gas demand to 2015 (CER 2008).

Significantly, the Irish Government has also set firm targets of deriving 15% of its electricity from renewable sources by 2010, and 33% by 2020 (DCMNR 2007). In October 2008, the

target for 2020 was revised upwards to 40% (DEHLG 2008). A comprehensive All-Island Grid Study commissioned by the renamed Department of Communications, Energy and Natural Resources indicated that renewable penetration levels of up to 50% were technically and economically viable (DCENR 2008). Given the projected growth in wind generation in the coming decade (Eirgrid 2007), it is quite possible that even the revised 2020 target will be exceeded. Such a scenario is included in the grid development plan published by Eirgrid, the transmission system operator (TSO), in October 2008 (EirGrid 2008a).

Work is also progressing on reinforcing the existing electrical interconnection to Northern Ireland, and on the construction of a new 500 MW interconnector to the UK, due for completion in 2012 (EirGrid 2008b). Finally, base load generation is provided by coal-fired plant, burning coal imported from a broad geo-political spectrum (O'Leary 2007a), and therefore relatively robust to price and supply shocks.

In summary therefore, the Irish electricity systems has significantly better security of supply (SoS) than the transport sector; if the transport sector continues to rely almost 100% on oil, this disparity is likely to increase significantly over the next decade. Hence, electrification of the Irish transport sector would increase the SoS of its energy supply, and reduce exposure to oil price and supply shocks. Given the recent and projected improvements in the efficiency and Carbon-intensity of electricity supply, it is of interest to quantify the potential effect of electrification on sectoral and national PER and GHG emissions, and to examine some of the impacts on the electricity system of such additional load. These issues are addressed in the following section. Although the specific calculations presented here apply to Ireland only, the general methodology is, of course, generally applicable.

Quantifying the electrical energy requirement

In order to quantify the potential demands on the electrical system of an electrified transport system, it is necessary first to quantify the energy required to physically move a vehicle. The following analysis focuses exclusively on passenger cars (PC), because that is where international research and development effort is overwhelmingly targeted. An immediate difficulty arises: the energy required to move a vehicle depends both on the physical characteristics of the vehicle – mass, frontal area, drag coefficient, engine and transmission efficiency – and on the nature of the drive cycle: peak speed, number and severity of accelerations, percentage of time at idle, etc. Since vehicle and drive-cycle characteristics vary geographically, temporally, and with driving style, it is not possible to establish a definitive answer to this question, and data gathered in disparate geographical regions may not be transferable directly to the Irish situation. Nonetheless, such data does provide a valid and useful contextual framework for local estimates.

The principal approach adopted in this work was to develop a simple model to determine the minimum theoretical energy required to move a given vehicle a fixed distance over a specified drive cycle. The model was then used to calculate the minimum energy requirement (MER), in Wh.km<sup>-1</sup>, of a range of vehicles representative of the Irish PC fleet, operating over a selection of legislative and real-world drive cycles. These findings are compared to estimates obtained in US studies.

#### Outline of the modelling process

The model employed in this work is spreadsheet-based, and very much simpler than the ADVISOR or PSAT models developed by the US National Renewable Energy Laboratory (NREL). A simpler model can be employed because no attempt is made to optimise, or to directly determine, drive train efficiency or exhaust emissions; the focus is purely on calculating the minimum energy requirement. Nonetheless, much interesting information emerges from the exercise.

The model is driven by the speed-time profile of the specified drive cycle. At each time step, the model calculates the tractive effort required at the tyre-road interface to overcome the opposing forces of aerodynamic drag and rolling resistance, and the inertial force required to follow the speed-time profile (which may be opposed to, or in the direction of, vehicle movement). Integrating the tractive effort with respect to distance travelled yields a theoretical minimum energy requirement for the cycle – assuming that 100% of braking energy is recovered and can be regenerated with no losses. For conventional vehicles (i.e. with zero regeneration), the energy dissipated in the braking process must be added back, yielding a higher theoretical energy requirement.

Six vehicles were simulated in total; their relevant characteristics are summarised in Table 1. The Polo, Golf, and Passat represent the classes of vehicle which dominate the Irish PC fleet. The VW Tiguan and VW Touareg were simulated since they are representative of compact and large SUV designs, respectively, that have begun to penetrate the Irish market since 2000. The final vehicle modeled was the Toyota Prius.

	<b>Polo</b>	<b>Golf</b>	<b>Passat</b>	<b>Prius</b>	<b>Tiguan</b>	<b>Touareg</b>
<b><i>Drag coefficient</i></b>	0.32	0.31	0.29	0.26	0.37	0.41
<b><i>Frontal area (m<sup>2</sup>)</i></b>	2.04	2.22	2.26	2.15	2.54	2.78
<b><i>mass (kg)</i></b>	1003	1281	1457	1300	1590	2301
<b><i>Rolling resistance coefficient</i></b>	0.01					

**Table 1 Principal characteristics of the vehicles for which drive cycle minimum energy requirement (MER) was calculated**

The vehicles were “driven” through four test cycles: the New European Drive Cycle (NEDC), the legislative cycle used within the EU to determine emissions rates and fuel consumption for vehicle type approval; US06, an American drive cycle designed to test vehicle emissions and fuel consumption at high speeds and aggressive driving conditions; ARTEMIS urban, and ARTEMIS motorway 130 – drive cycles developed under the EU ARTEMIS programme, which was established to determine, via direct measurement, drive cycles representative of

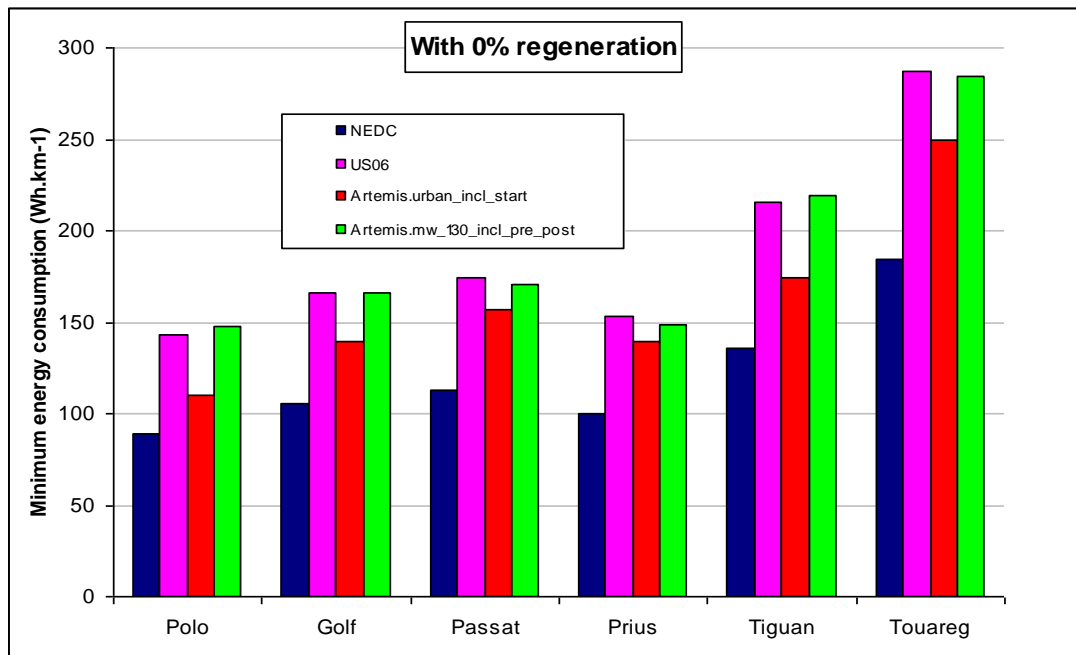
real-world driving conditions in the EU. The former represents driving under urban conditions; the latter, motorway conditions with a peak vehicle speed of 130 km.h<sup>-1</sup>. The speed-time trace data for all cycles was obtained from ARTEMIS (2008).

#### Model results

The main results from the model are summarised in Figure 1 and Table 2 below. Four features of the graph are immediately evident: first, the minimum energy requirement of the NEDC is significantly lower than that for the other three cycles – it is probable, therefore, that the fuel consumption and CO<sub>2</sub> emissions measured on the NEDC will underestimate those obtained under real-world conditions. Second, the minimum energy requirement (MER) for the two SUVs is approximately 50% greater than for their corresponding conventional models. Third, the MER for the Prius is lower than that of the Golf and Passat by about 10%, particularly on the high-speed cycles – this is a consequence of its low drag coefficient. Finally, the MER for the classes of vehicle that constitute the bulk of the Irish PC fleet – Polo, Golf, and Passat – lies somewhere between 90 and 180 Wh.km<sup>-1</sup>. For the two ARTEMIS cycles, the MER ranges from 110 to 170 Wh.km<sup>-1</sup>.

	<b>Polo</b>	<b>Golf</b>	<b>Passat</b>	<b>Prius</b>	<b>Tiguan</b>	<b>Touareg</b>
<b><i>NEDC</i></b>	88.6	105.5	113.3	99.7	135.4	184.4
<b><i>US06</i></b>	142.8	165.9	174.6	153	215.6	287.3
<b><i>ARTEMIS urban</i></b>	110.3	139.3	157	139.7	173.9	249.1
<b><i>ARTEMIS mway 130</i></b>	147.3	166.4	170.4	148.5	219.3	284.6

**Table 2 Minimum energy requirement (Wh.km<sup>-1</sup>) by vehicle and drive cycle**



**Figure 1 Minimum energy consumption by vehicle and drive cycle**

To put these values in context, it is useful to compare them with the data presented in Tate et al (2008). That study estimated a MER of  $240 \text{ Wh.km}^{-1}$  for the US06 cycle, although the vehicle parameters are not specified. However, it is within the range of values computed above. More interestingly, perhaps, the authors of that study also used a sophisticated model to estimate the MER for a sample of 600 real-world drive cycles collected as part of the Southern California Association of Governments Regional Travel Survey (SCAG RTS). It was found that the vast majority of real-world cycles analysed had a MER of  $150\text{-}250 \text{ Wh.km}^{-1}$ . This is somewhat higher than the  $110\text{-}170 \text{ Wh.km}^{-1}$  estimated using the ARTEMIS cycles for the Polo, Golf, and Passat vehicles, but that is not unexpected given the geographical and cultural disparities between the regions concerned. Similarly, Kalhammer et al (2007) estimated the energy requirement at  $200 \text{ Wh.km}^{-1}$ , although it is not clear if this is energy delivered to the tyre-road interface or extracted from the on-board energy store. Stephan and Sullivan (2008) calculate an estimate of  $256 \text{ Wh.km}^{-1}$  of wall-socket energy for the US PC fleet; as shown below, this corresponds to an MER of about  $190 \text{ Wh.km}^{-1}$  at the tyre-road interface.

To date, no definitive drive cycle data has been gathered for Ireland so estimation of the MER for a representative cycle is subject to significant uncertainty; as stated previously, it is likely that the NEDC under-estimates the MER of real-world drive cycles. As an initial estimate, it is possible to compare the real-world fuel consumption of the Irish PC fleet – derived from NCT-recorded PCkm (Howley et al 2007a), and national fuel consumption data (Howley et al 2007b) – with the fleet-average NEDC fuel consumption. On the basis of these data, this author calculates the real-world, primary energy consumption of the Irish PC fleet at 750 Wh.km<sup>-1</sup>, compared with an NEDC value of 660 Wh.km<sup>-1</sup> – a difference of 15%. Increasing the NEDC MER of each vehicle by this amount yields the following Table:

"Irish" drive cycle (NEDC + 15%)						
	Polo	Golf	Passat	Prius	Tiguan	Touareg
<b>MER (Wh.km<sup>-1</sup>)</b>	101.9	121.3	130.3	114.7	155.7	212.1

Table 3 Minimum energy requirement, by vehicle, for “Irish” drive cycle (Wh.km<sup>-1</sup>)

Based on the foregoing, a preliminary MER estimate of 130 Wh.km<sup>-1</sup> for the Irish PC fleet doesn’t seem unreasonable. These figures represent the energy that must be supplied at the tyre-road interface; of more practical interest is the electrical energy that must be extracted from a wall socket – the wall socket energy requirement (WSER). Two factors impact significantly on the relationship between MER and WSER: the first – inefficiencies between the wall socket and the tyre-wheel interface – tends to increase the WSER of the vehicle; the second, regenerative braking, tends to reduce the WSER. These two factors will now be examined.

Inefficiencies between wall socket and tyre-road interface

A schematic diagram of the energy flows of a PHEV is presented in **Error! Reference source not found.** It is clear that each electrical device constitutes a source of exergy loss

between the wall socket and the tyre-road interface. In practice, the efficiency with which electrical power is transmitted through each device in the chain is a complex function of the current flow through, and voltage across, its terminals. For simplicity, fixed values are assumed in the calculations presented here. Although by no means definitive, they are representative of values currently achievable at acceptable cost (e.g. AC Propulsion 2008, Duvall 2005, EPRI 2007, Nelson and Khalil 2006, Pesaran et al 2007, Shidore et al 2007).

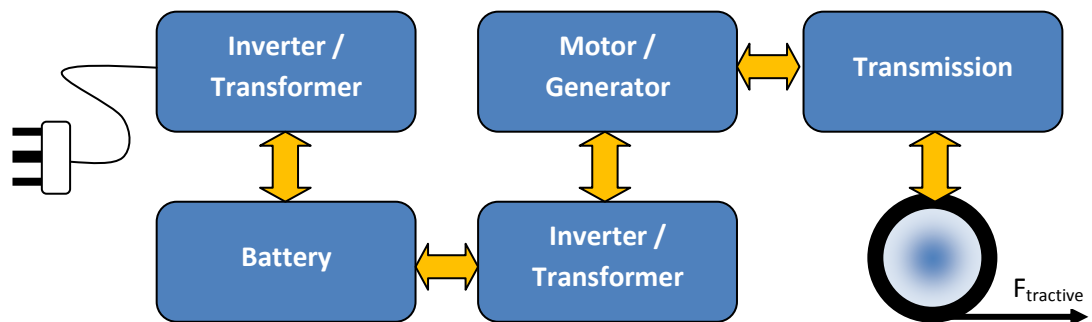


Figure 2 Schematic layout and energy flows for PHEV

Assumed efficiency values	
<i>Transformer / Inverter</i>	95%
<i>Battery: current input or output</i>	97%
<i>DC machine in Motor mode</i>	90%
<i>Mechanical Transmission</i>	98%
<i>DC machine in Generator mode</i>	85%
<i>Wall socket to wheel efficiency</i>	75%
<i>Wheel to battery regenerative efficiency</i>	77%

Table 4 Component efficiency values assumed for operation in electric mode

Notwithstanding these caveats however, using the indicated values it is clear that only 75% of the energy drawn from the socket is delivered to the tyre-road interface. This crude estimate matches that suggested as reasonable in Tate et al (2008). Therefore, based on an MER of 130 Wh.km<sup>-1</sup>, wall-socket electrical requirement (WSER) for Irish PC would be approximately 175 Wh.km<sup>-1</sup> on a cycle representative of real-world Irish conditions.

## Efficiency gains through regenerative braking

It will be noted in **Error! Reference source not found.** that the energy flow vectors between battery and wheel are bi-directional. This is because a key attribute of vehicle electrification is the ability to exploit regenerative braking, i.e. the capacity to store, as electrical energy in the battery, some of the kinetic energy normally dissipated by the braking system. Once again, energy losses occur between tyre and battery: a quick calculation using the values in Table 4 yields an overall efficiency of 77%. Tate et al (2008) suggest a lower figure of 60%, without stipulating why this should be so. However, where only one pair of wheels is mechanically coupled to the motor-generator, it may be necessary to dissipate some fraction of the vehicle kinetic energy via frictional brakes. Moreover, their analysis of drive-cycle data suggests that energy dissipation rates in real-world use may sometimes exceed the electrical power capacity of the vehicle systems, and that mechanical dissipation may therefore be required to defray some fraction of the theoretically recoverable energy.

In any event, analysis of the data from the simplified model presented here show that the drive-cycle profile is by far the dominant determinant of regeneration system effectiveness. Figure 3 indicates the fraction of the MER required for the drive cycle that could theoretically be recovered – assuming zero losses in the regenerative braking systems – for storage in the battery. It can be seen that there is very significant variation, from 10% for the Polo class vehicle on the ARTEMIS motorway cycle, to almost 70% for the Passat and Prius class on the ARTEMIS urban cycle.

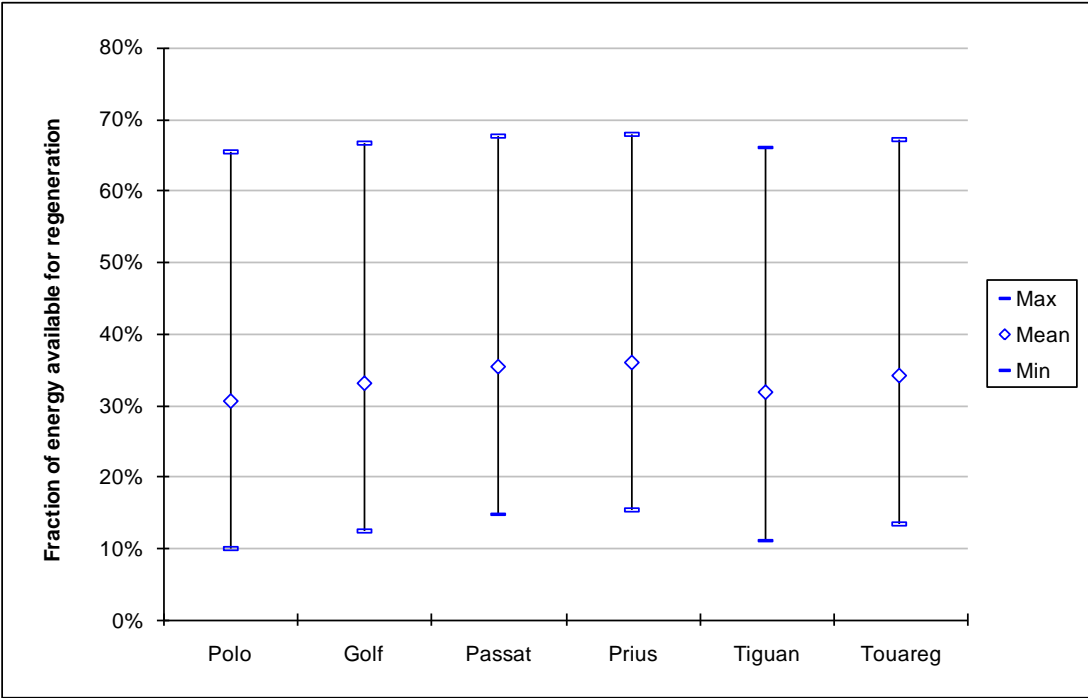


Figure 3 Fraction of drive-cycle energy theoretically available for regeneration

Assuming that a representative Irish drive cycle is 15% more energy-intensive than the NEDC, and that the additional energy is proportionally split between aerodynamic, road, and braking losses, the MER for the cycle can be calculated for any level of regeneration. Finally, if we adopt the assumption of Tate et al (2008) that 60% of theoretical regenerative energy is recovered in practice, we obtain the following:

"Irish" drive cycle (NEDC + 15%)						
MER (Wh.km <sup>-1</sup> )	Polo	Golf	Passat	Prius	Tiguan	Touareg
<b>0% regeneration</b>	101.9	121.3	130.3	114.7	155.7	212.1
<b>100% regeneration</b>	76.7	88.0	91.2	79.6	115.0	151.2
<b>60% regeneration</b>	86.8	101.3	106.8	93.4	131.3	175.6

Table 5 Minimum energy requirement, by vehicle, for "Irish" drive cycle, with and without regeneration (Wh.km<sup>-1</sup>)

Based on Table 5, a realistic estimate of the MER for a PHEV on the Irish drive cycle appears to be about 105 Wh.km<sup>-1</sup>. Allowing for inefficiencies between the wall socket and the tyre-road interface (75% energy transfer efficiency), this increases to about 140 Wh.km<sup>-1</sup>, the wall socket electrical energy requirement (WSER) that will be assumed throughout the rest of this paper for all PHEV entering the Irish PC fleet. Comparable WSER estimates include 160 Wh.km<sup>-1</sup> for the forthcoming VW Golf TwinDrive (Volkswagen AG 2008); 150 Wh.km<sup>-1</sup> for the forthcoming BlueZERO E-Cell and E-Cell Plus from Mercedes-Benz (Green Car Congress 2008b); 256 Wh.km<sup>-1</sup> for US PHEV (Stephan and Sullivan 2008); and 163-278 Wh.km<sup>-1</sup> for a US mid-sized sedan on the UDDS, HWFET, and US06 drive cycles (Johnson 2008).

However, as can be seen from the range of values estimated by Johnson, WSER is quite sensitive to drive cycle characteristics. On a predominantly urban cycle the WSER is much lower; on the urban component of the NEDC (ECE-15), for instance, the WSER of a representative PC is 95 Wh.km<sup>-1</sup> – a reduction of 40%. In practice, WSER will vary between regions and with time of year. The precise value is less important than the fact that – as

shown below – it is considerably lower than the primary energy requirement for vehicles using ICE alone.

Primary energy requirement under electric versus fossil-fuelled power

As previously demonstrated, the real-world primary energy requirement of the Irish PC fleet is approximately 750 Wh.km<sup>-1</sup>. It is not appropriate, however, to compare this value directly with the WSER of 140 Wh.km<sup>-1</sup> for a vehicle operating in electric mode, since the wall-socket electricity must first be generated, transmitted, and distributed. In 2006, the Irish electricity supply efficiency was 41.6% (Howley et al. 2008). The WSER therefore translates to a *primary* energy requirement of 337 Wh.km<sup>-1</sup> – less than half that required by conventional PC. These figures are summarized in Table 6.

	NEDC	“Irish” drive cycle
<b><i>EV MER (60% regeneration) (Wh.km<sup>-1</sup>)</i></b>	93	107
<b><i>EV WSER at wall socket (Wh.km<sup>-1</sup>)</i></b>	124	140
<b><i>EV PER for electricity supply (Wh.km<sup>-1</sup>)</i></b>	298	337
<b><i>Conventional PC MER (no regeneration) (Wh.km<sup>-1</sup>)</i></b>	113	130
<b><i>Calculated PC PER (Wh.km<sup>-1</sup>)</i></b>	660	750
<b><i>EV PER, relative to PC</i></b>	45%	

Table 6 Energy requirement of PHEV, and conventional PC on NEDC and “Irish” drive cycles

Hence, operation of a grid-powered electric vehicle (EV) on an Irish drive cycle will reduce the primary energy requirement of the vehicle by about 55% on the NEDC, given the supply efficiency of the Irish electricity grid in 2005 (41%). As discussed earlier however, penetration of renewables into the Irish generation mix is growing rapidly. The Government has set a target of 15% of electricity generation from renewable sources by

2010, and in October 2008 revised the 2020 target up to 40% (DEHLG 2008). Achieving these targets will increase the efficiency of electricity supply (relative to fossil fuel inputs) to about 45% and 64% respectively, once allowance is made for the expected increase in total electrical demand at those dates. The effect this will have on the PER of an EV is shown in Figure 4.

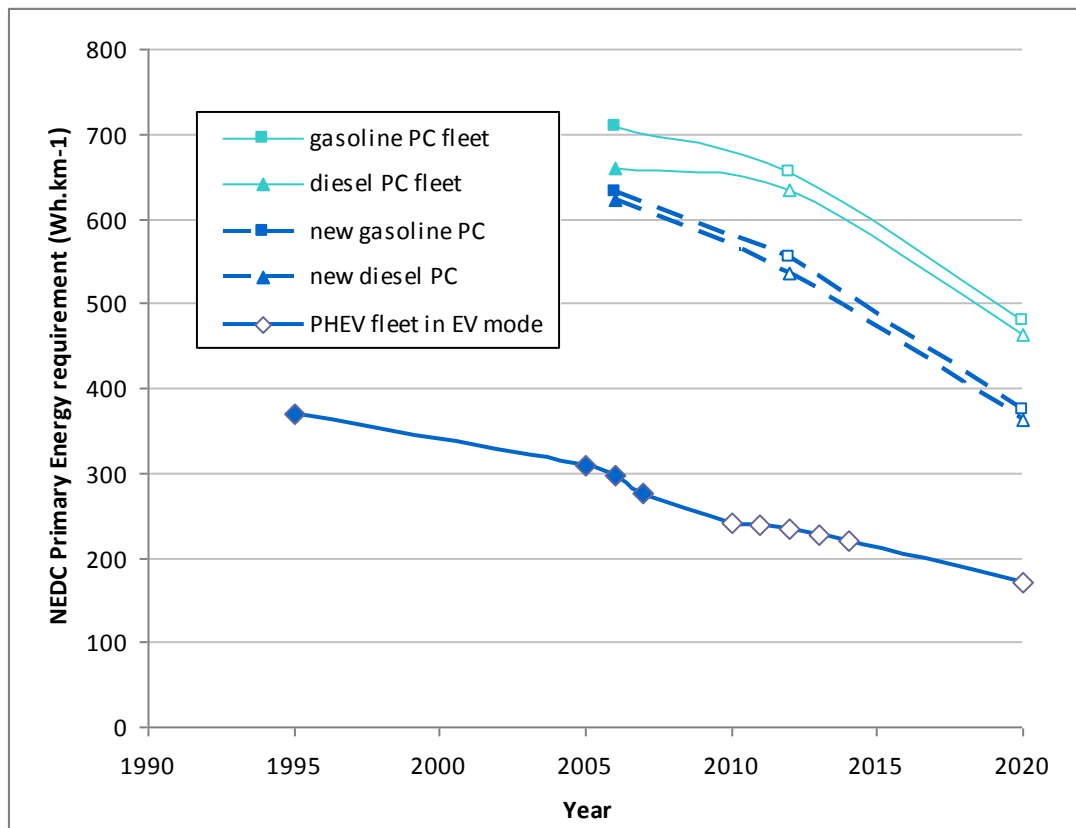


Figure 4 Primary energy requirement of PHEV in EV mode, and conventional PC, on the NEDC. Solid symbols denote historic data, others are projected. Dashed lines link values for new vehicles only; solid lines represent fleet averages. New cars are assumed to meet proposed EU CO<sub>2</sub> targets of 130 g.km<sup>-1</sup> and 95 g.km<sup>-1</sup>, in 2015 and 2020 respectively.

Figure 4 also shows the fossil energy requirement of new gasoline and diesel cars entering the Irish fleet in 2006. The EU initially proposed plans to impose on manufacturers a mandatory, fleet-averaged, CO<sub>2</sub> limit of 130 g.km<sup>-1</sup> (on the NEDC) in 2012, with a further limit of 95 g.km<sup>-1</sup> by 2020 (Commission of the European Communities 2007). Following

extensive negotiations with car manufacturers, the  $130 \text{ g.km}^{-1}$  limit will now be phased in between 2102 and 2015 (European Parliament 2008). Assuming that new PC entering the Irish fleet match these limits, the corresponding energy requirement of those vehicles (on the assumption that they are conventionally powered) can be calculated – these are joined with dashed lines in Figure 4. Of more relevance is the resulting energy intensity of the conventional PC fleet (upper solid lines in Figure 4), which is seen to be substantially higher than that of the newest vehicles; the performance of the fleet as a whole lags that of the newest vehicles by about 8-10 years. This is a crucial differentiating factor between grid-powered and conventional PC: with grid-powered vehicles, any improvement in electrical supply efficiency or  $\text{CO}_2$  intensity is immediately transmitted throughout the entire EV fleet.

It is clear that, by 2020, use of a PHEV in EV mode would reduce the vehicle's fossil-fuel PER (on the NEDC) to less than one third of that required by a conventional PC in 2006. In fact, even using the 2006 Irish electricity-generation mix, NEDC PER is less than that projected under EU proposals for new PC in 2020. As an additional benefit, the fossil fuel used to generate the electricity comprises a variety of fuels obtained from a broad spread of geopolitical regions, thereby reducing very significantly the oil-dependence of the Irish passenger car fleet, and improving its security of supply.

#### $\text{CO}_2$ emissions for EV versus ICEV

A similar analysis can be carried out with respect to  $\text{CO}_2$  emissions from PC operating in EV mode. In 2006, the  $\text{CO}_2$  emission intensity of Irish electricity generation was  $601 \text{ g.kWh}^{-1}$  (Howley et al 2007b). As the share of electricity derived from renewable sources increases, and the proportion of electricity derived from coal and peat decreases due to increased total demand, the  $\text{CO}_2$  emission intensity will continue to decrease. Figure 5 shows the variation in  $\text{CO}_2$  intensity of the Irish electricity supply, as a function of renewables

penetration. Also shown are the targeted levels of renewable generation in 2010 (15%) and 2020 (40%). A strong downward trajectory in CO<sub>2</sub> intensity is clearly evident.

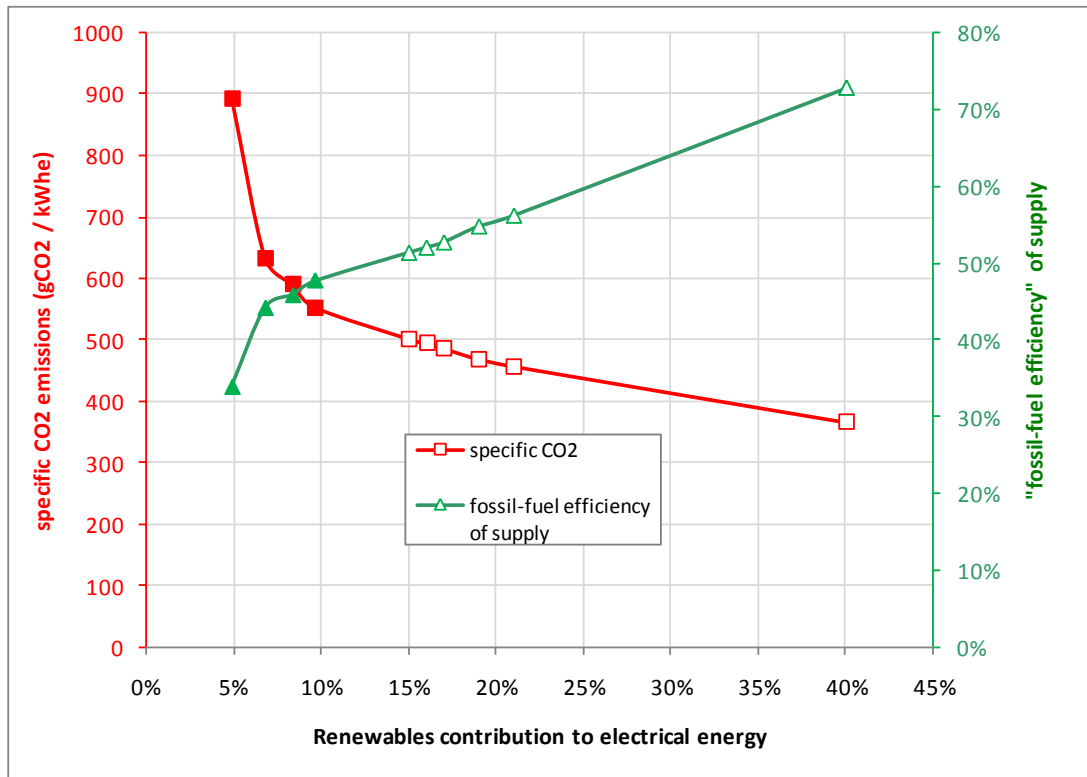


Figure 5 Specific CO<sub>2</sub> emissions, and “fossil-fuel efficiency” of Irish electricity supply, as a function of renewable contribution to supply. Solid symbols denote historic data (1995, 2005, 2006, 2007).

Using the WSER values developed above, of 124 Wh.km<sup>-1</sup> for EV on the NEDC, or 140 Wh.km<sup>-1</sup> on the “Irish” drive cycles respectively, calculation of the CO<sub>2</sub> emissions (g.km<sup>-1</sup>) from PHEV operating in EV mode is straightforward. The results are presented in Figure 6. The EV data for the NEDC is compared with corresponding data from Howley et al (2007a) for PC entering the Irish fleet in 2006.

CO<sub>2</sub> data for conventional PC on the “Irish” drive cycle is not directly available, and was computed using the same method applied to calculation of real-world energy intensity: for historic values, national PCKm data derived from NCT recordings (Howley et al 2007a), and

national fuel consumption data (Howley et al 2007b), were combined with CO<sub>2</sub> emission factors for gasoline and diesel (Howley et al 2007b) to estimate the real-world CO<sub>2</sub>-intensity of the Irish PC fleet. CO<sub>2</sub> emissions from future conventional vehicles (CV) were estimated using a linear interpolation between the known NEDC values for new CV in 2006 (Howley et al 2007b), and the limit values agreed by the EU for new CV entering the market in 2015 (130 g.km<sup>-1</sup>) and 2020 (95 g.km<sup>-1</sup>) (European Parliament 2008). Values for the CV fleet – as opposed to new CV – were calculated using simple fleet replacement model described below. All NEDC values were increased by 15%, to reflect the higher energy demand of the real-world, Irish drive cycle. The results are presented in Figure 6 and Figure 7.

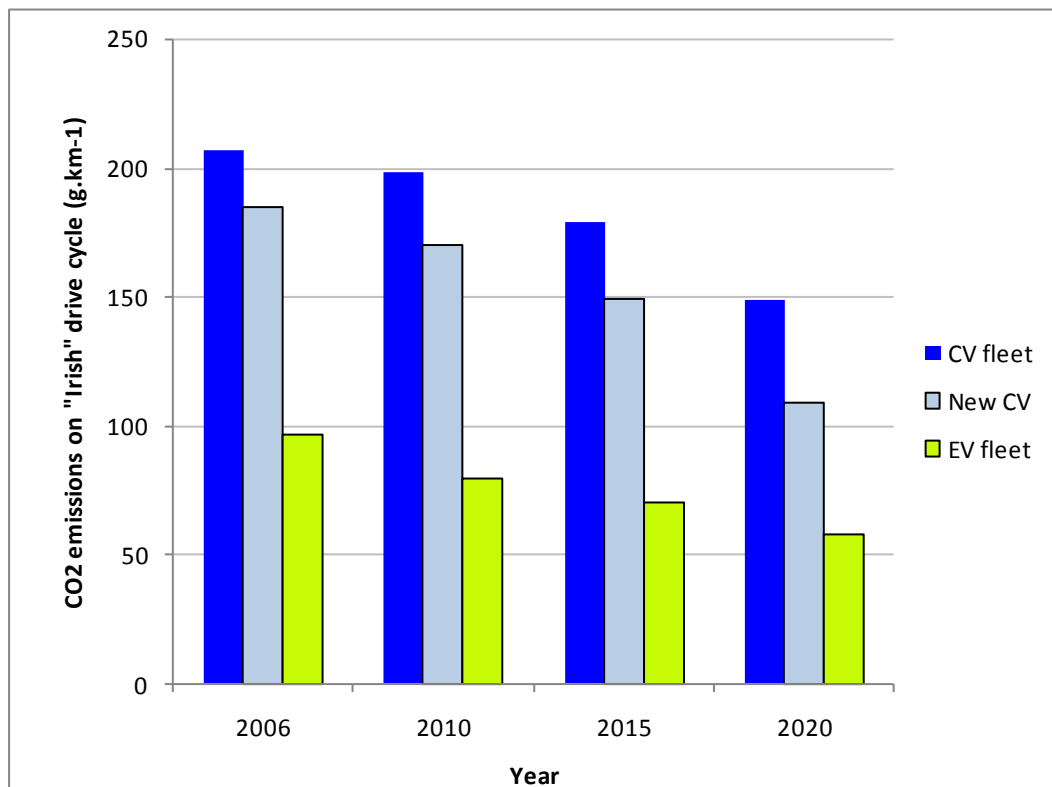
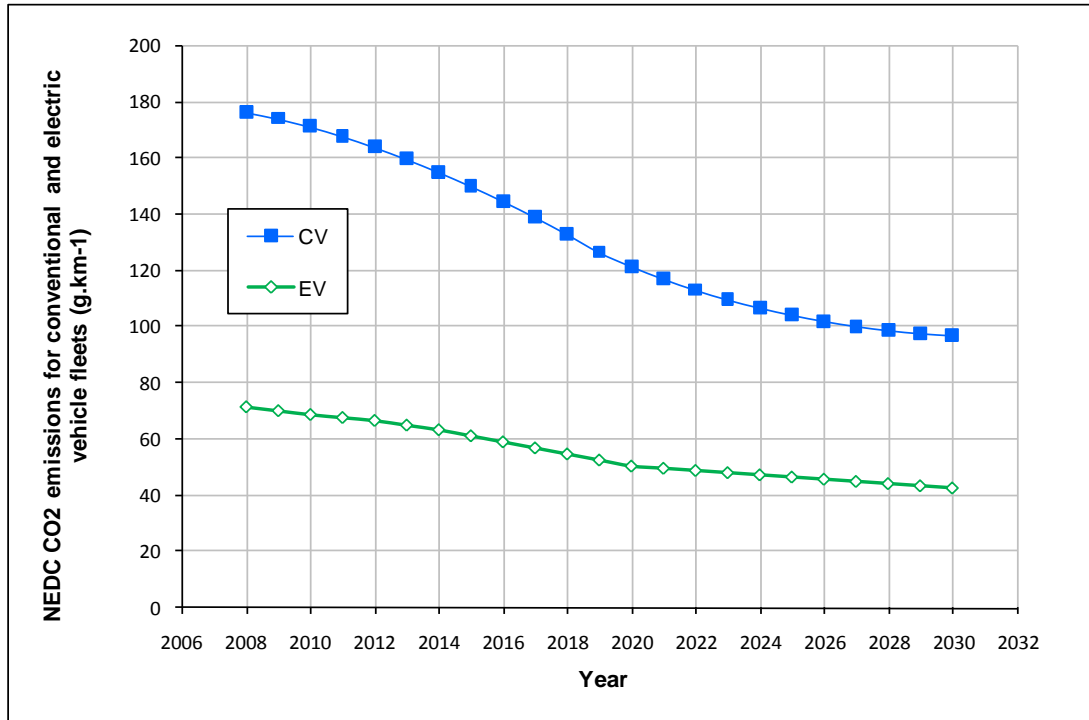


Figure 6 CO<sub>2</sub> emissions (g.km<sup>-1</sup>) from conventional gasoline and diesel PC entering the Irish fleet in 2006, compared with emissions from grid-powered EV. For EV, emissions are calculated based on the Irish electricity mix in 2006, and the projected mix in 2010 and 2020.



**Figure 7 Average CO<sub>2</sub> intensity of conventional vehicle (CV) fleet and EV fleet on NEDC**

In summary, switching to grid-powered EV would reduce the PER of the Irish PC fleet by over 50% for each km travelled in EV mode. CO<sub>2</sub> intensity would also decrease by more than 50% – based on 2006 electricity supply characteristics – and security of supply for the transport sector would be significantly increased. Projecting forward to 2020, by which time a significant level of PHEV penetration would be possible, grid-powered EV offer the potential to further reduce PER- and CO<sub>2</sub>-intensity, down to about 30% of 2006 values.

It is worth noting that the CO<sub>2</sub> emissions and PER assigned to PHEV in the foregoing calculations are based on grid-average values. In Ireland, the base load electrical requirement is met using coal and peat fired generation. Incremental load imposed by PHEV – especially if load scheduling can be influenced by the TSO – would probably be met using a combination of wind generation and high-efficiency, natural-gas-fired, GTCC plant. The true PER- and CO<sub>2</sub>-intensity of the electricity supplied to PHEV would therefore be considerably (perhaps as much as 50%) lower than indicated in the Tables and Figures presented here.

## Electrical energy requirement of PHEV

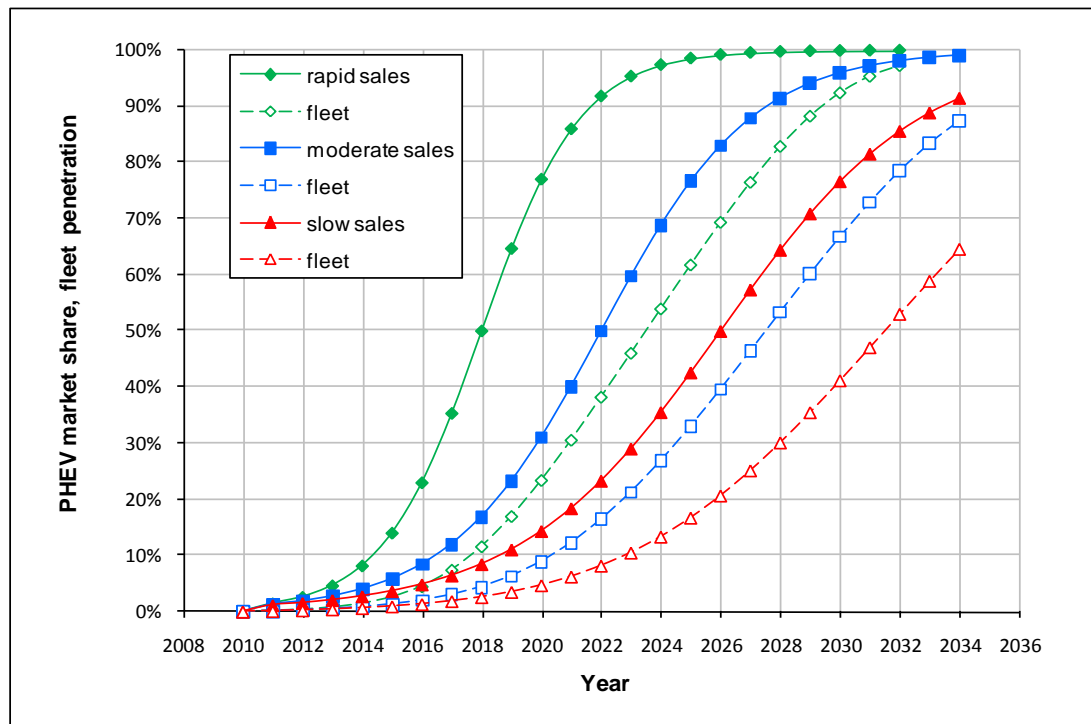
In order to determine the capacity of the Irish grid to support a fleet of PHEV, it is necessary to determine a corresponding daily energy requirement. That depends on the size of the PHEV fleet, and on the number of km each PHEV completes in electric mode.

## Size of the PHEV fleet

In 2007, the most recent year for which data is available, the Irish PC fleet numbered just under 1.9 million vehicles, of which none are classified as EV or PHEV (Department of Transport 2008b). Given market constraints, it will take some time for significant PHEV penetration to occur. Accurate prediction of the rate of penetration is difficult, but the trend is likely to follow the classical “S-curve” form of the logistic curve. Given this assumption, the shape of the curve is completely determined if one specifies the number of years required to grow market share to 50%. Coupling the above with two further simplifying assumptions – constant fleet size, and a fixed vehicle lifetime of twelve years – the future penetration rate of PHEV in the PC fleet can be estimated.

Three scenarios were investigated: a “rapid” growth case, whereby PHEV accounted for 50% of all PC sales (i.e 50% market share) by 2018; a “moderate” case, in which 50% market share is achieved by 2022; and a “slow” case, in which 50% market share is delayed until 2026. It should be noted that market share refers to fleet additions only – achieving 50% penetration of the PC fleet requires significantly longer. Assuming PHEV sales commence in 2011, the variation in market share and fleet penetration for each of the three scenarios is shown in Figure 8. To put these scenarios in context, in September 2008 Chrysler forecast that “at least 50 percent of the market” will consist of pure EVs or extended-range electric vehicles (EREVs) by around 2020 (Burgess 2008) – slightly ahead of the “moderate” scenario. In November 2008, the Irish Ministers with responsibility for

Transport and for Energy announced a “target of 10% of all vehicles in the transport fleet to be powered by electricity by 2020” (Dempsey 2008), again slightly ahead of the “moderate” scenario. Google’s “Clean Energy 2030” proposal envisages a slightly later start date of 2013 for PHEV sales; projected sales growth rate is slightly ahead of the “moderate” scenario (Greenblatt 2008). Finally, in November 2008 Germany announced that it was aiming to put one million electric (EV) and plug-in (PHEV) vehicles on the road by 2020 and 10 million by 2030 – that corresponds closely to the “slow” scenario (Green Car Congress 2008a).



**Figure 8 Three projections for PHEV sales growth, and consequent PC fleet penetration, with sales commencing in 2011: “rapid” = 50% share of sales by 2018; “moderate” = 50% by 2022; “slow” = 50% by 2026.**

Fraction of trip km completed in EV mode

Penetration of PHEV into the PC fleet addresses only one aspect of the situation since, by definition, PHEV do not operate solely on electric power. The question of how many km a

PHEV will complete in electric (EV) mode is somewhat intractable, since it depends on trip length and kinematic profile, and on the vehicle characteristics. In respect of the latter, both the energy storage capacity of the vehicle battery, and the power capability of the entire electric drive train (as shown by Tate et al), are particularly significant. Power flow constraints tend to increase drive-cycle PER (since less of the regenerative braking potential is realised), and may also require use of ICE to provide power boost during vehicle accelerations. The degree to which the electric power flow is constrained is a fundamental design decision, and will vary between manufacturers and market segments. Some manufacturers are planning for 100% performance capability in EV mode – these include General Motors with the Volt (Tate et al 2008), and VW with the TwinDrive (Winterkorn 2008). Others, including Toyota, are evaluating PHEV with reduced performance capability in EV mode – the Prius III, for instance, is expected to require ICE operation at speeds above  $100 \text{ km.h}^{-1}$  (Toyota 2007). It is the view of this author that, with increasing electrification of the automobile, the power flow constraint will cease to apply: the PC will evolve from conventional ICE-only vehicle, through mild hybrid, to what GM terms the extended-range electric vehicle (EREV) – a full-EV-capability, series-architecture PHEV, where the role of the ICE is simply that of range extension<sup>1</sup>. This is a vision shared by General Motors (Tate et al 2008), Chrysler (Burgess 2008), VW (VW 2008), and Chinese manufacturer BYD (Balfour 2008). For simplicity therefore, the calculations presented in the remainder of this paper assume that operation in EV mode is constrained by AER only – electrical power constraints are neglected.

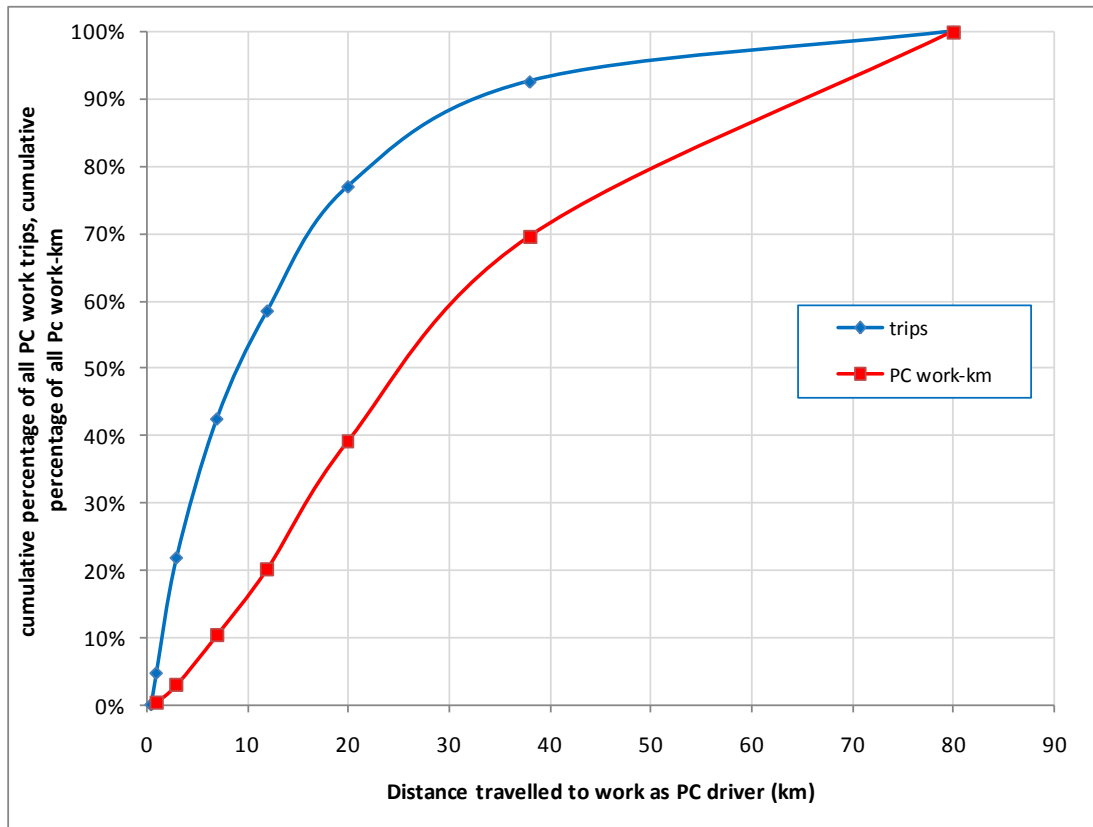
#### Estimation of Irish PC trip characteristics

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<sup>1</sup> The ultimate expression of this philosophy may lead to the replacement of the ICE range extender by a fuel-flexible fuel cell.

The energy- and CO<sub>2</sub>-intensity of a representative Irish drive cycle has previously been assumed as equivalent to NEDC + 15%. The average trip length, however, remains to be specified. Ireland does not have access to detailed time-speed data equivalent to that captured in the SCAG RTS analysed by Tate et al (2008). The most reliable and detailed source of information available, derives from Census data gathered in 2006 (CSO 2008b). Of this, the most relevant data pertains to the distance travelled to work, and on the mode of transport employed. The data related to travel by private car – as the driver – is summarized in Figure 9.

This information pertains to travel to and from work only. A quick calculation reveals that the total PCkm accounted for in the above data set amounts to only 30% or so of the annual PCkm estimated by SEI for 2006 using National Car Test data (Howley et al 2007a). It is by no means certain that the trip distance distribution for the remaining 70% corresponds to that shown in Figure 9. Nonetheless, in the absence of better information, the author felt obliged to make that assumption.



**Figure 9 Cumulative distribution of trips and PCkm for work trips in Ireland, based on 2006 Census data**

Given the assumptions above – i.e. that operation in EV mode is constrained by all-electric range (AER) only, that trip distance distribution follows that presented in Figure 9, and that EV mode will be employed whenever achievable – it is possible to determine the fraction of all PCkm that will be completed in EV mode for a given value of AER. The results are plotted in Figure 10. It is important to note that these results are based on the assumption that the PHEV is charged once per day; the infrastructural implications of this assumption are therefore relatively modest. The data points plotted in Figure 10 represent AER of 15, 25, 40, and 80 km. These values match well with the trip-distance categories used in the Census data. Coincidentally, they also represent realistic estimates of AER in the short to medium term. It is clear from Figure 10 that, given the assumptions made above, about 85% of all PCkm could be completed in EV mode given an AER of 80 km.

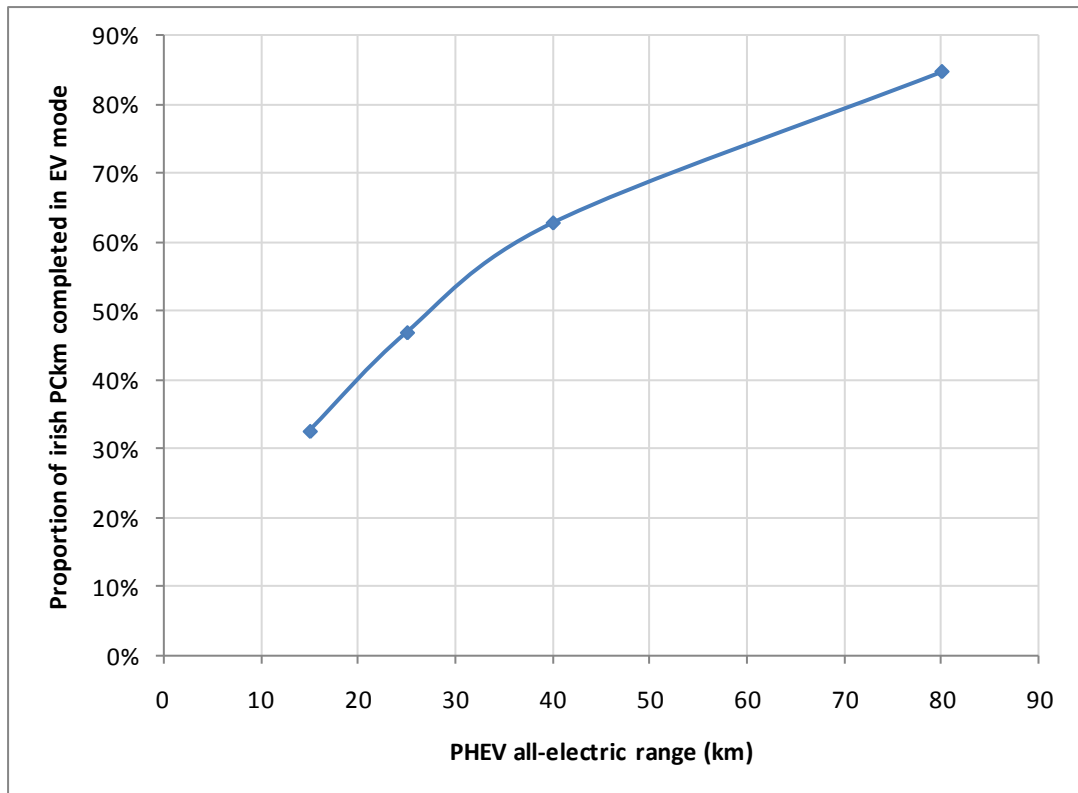
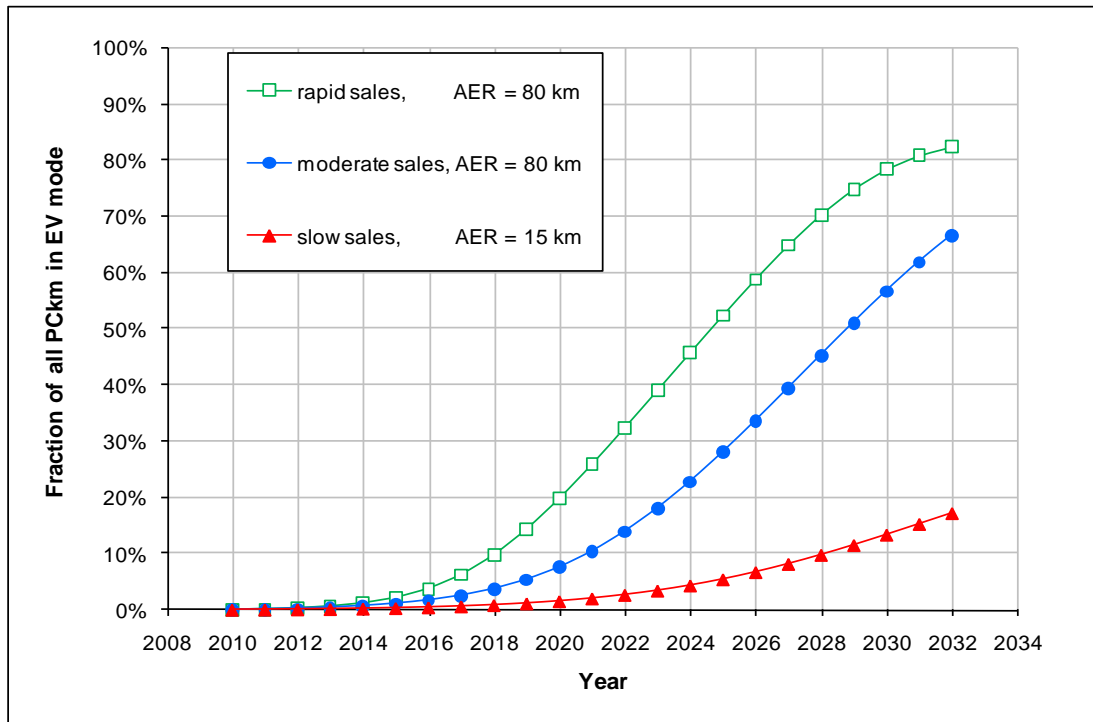


Figure 10 Impact of PHEV all-electric range (AER), on percentage of Irish PCkm completed in EV mode, based on author's analysis of 2006 census data

Finally, by combining the results presented in Figure 9 with fleet penetration data from Figure 8, the likely fraction of PCkm that will be completed in EV mode can be determined. As stated previously, this depends on the level of PHEV penetration in the PC fleet and on the AER of the PHEV. Figure 10 presents the calculations for three scenarios: an upper bound, based on rapid penetration of PHEV and AER of 80 km; a lower bound, based on slow penetration of PHEV and an AER of only 15 km; and an intermediate scenario in which PHEV fleet penetration proceeds moderately quickly but technology is sufficiently well developed by 2012-2015 to deliver an AER of 80 km. This last scenario is perhaps the most plausible.

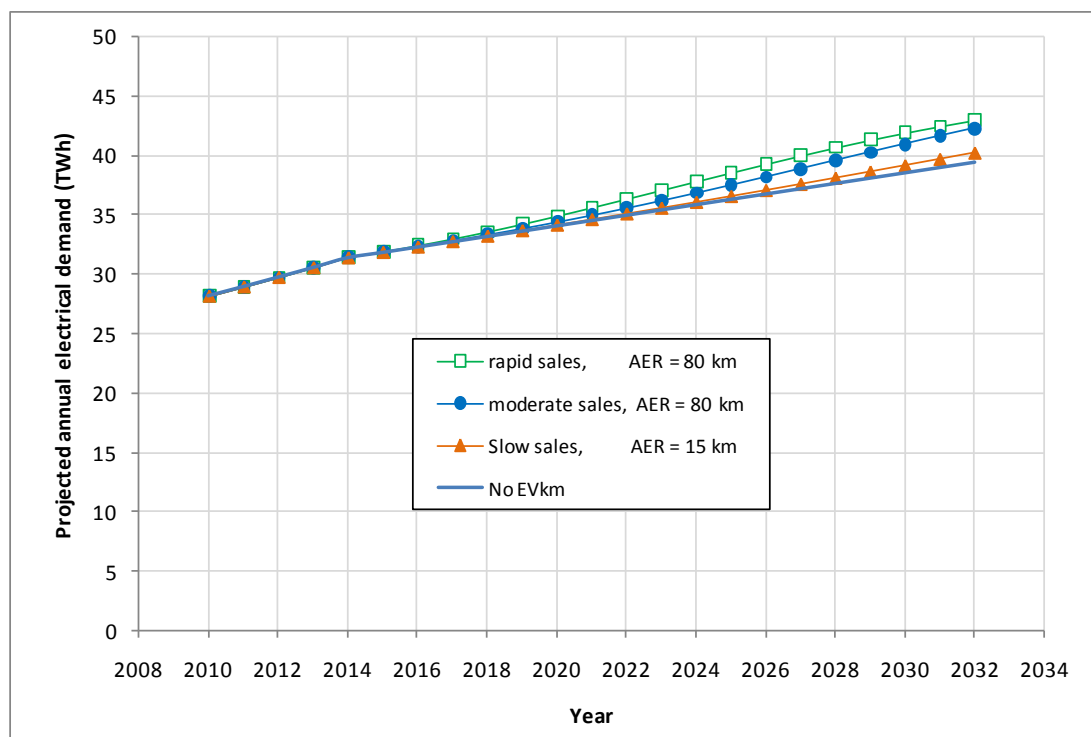


**Figure 11 Three projections for PCkm completed in all-electric (EV) mode, depending on growth rate of PHEV sales, and all-electric range (AER) of PHEV sold**

It is clear from Figure 11 that the fraction of PCkm completed in EV mode is very sensitive to both AER and fleet penetration. It is also apparent that, adopting even the most optimistic of these scenarios, only 20% of PCkm will be completed in EV mode by 2020; using the more plausible “moderate” scenario, the proportion drops to just 8%. Very significant penetration becomes possible, however, from 2020 to 2030.

Large-scale penetration of PHEV into the PC fleet may have significant implications for grid operation, and technologies such as smart metering and vehicle-to-grid (V2G) may have a significant role to play. Such considerations are beyond the scope of the current paper, but it is of interest to assess the change in total electrical demand that would accrue from the widespread adoption of PHEV. Given the assumed EV WSER of  $140 \text{ Wh.km}^{-1}$ , the PCkm data presented in Figure 9, Figure 10, and Figure 11, and an assumed increase in absolute PCkm of 1% per annum, the total annual electrical demand of the PHEV fleet can be computed. This is plotted, for each of the three scenarios previously discussed, alongside

projected baseline (zero EV) demand in Figure 12. It is evident that the impact on total annual electrical demand, at least to 2020, is modest – 0.5% to 2.5% – particularly in the context of a projected increase in baseline demand of 21% over the same period. It therefore seems reasonable to assume that the impact of PHEV penetration on grid performance and operation will be modest up to 2020 at least. Even by 2030, the “optimistic” scenario implies an increase of < 10% in annual electrical demand, relative to the projected baseline demand of 38.6 TWh in that year.



**Figure 12 Effect of PHEV fleet penetration and AER on projected annual electrical demand**

Impact of PHEV on national CO<sub>2</sub> emissions

Finally, Figure 13 and Figure 14 present the projected trend in CO<sub>2</sub> emissions of the Irish PC fleet under the assumption that PCkm increase by 1% or 2% per annum, respectively. For reference, this author’s analysis of National Car Test data suggests that Irish PCkm increased at an average annual rate of 4% from 2000-2006. That was unusually high, due to rapid economic growth and “decentralisation” of the housing market during the so-called “Celtic Tiger” era. EU data (European Commission 2008b) suggests that annual

growth in PCkm averaged about 1% per annum for the mature EU economies over the period 1990-2006. That seems a more plausible figure for Ireland over the coming decade.

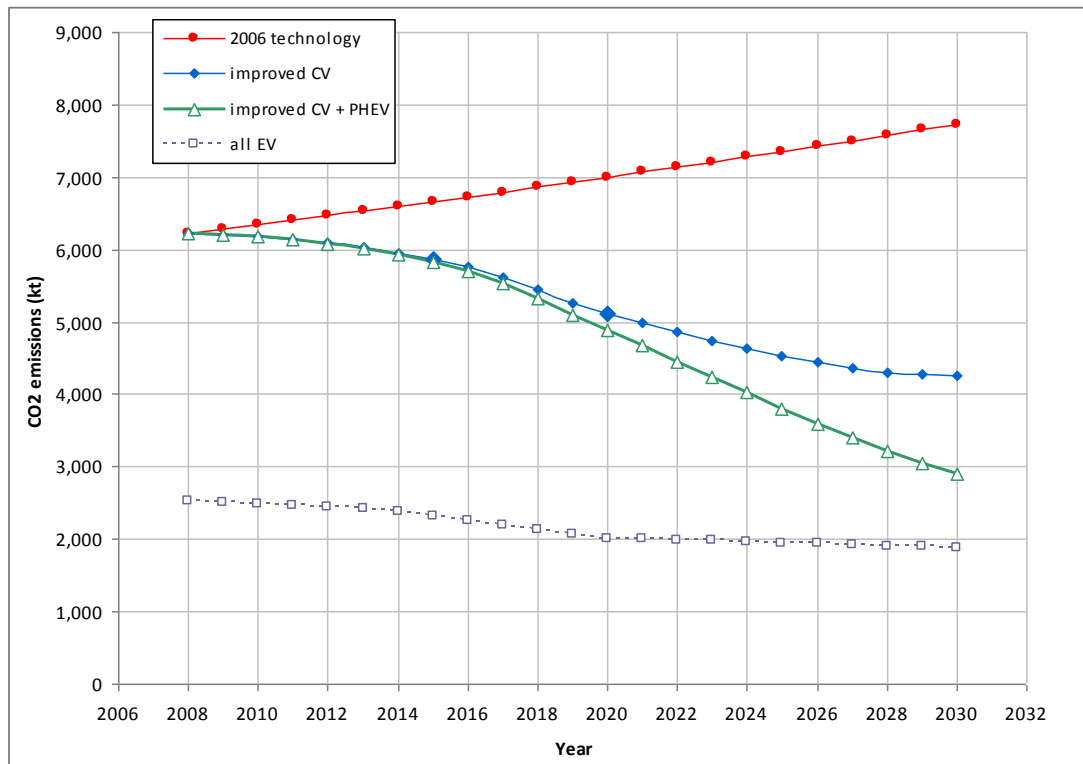
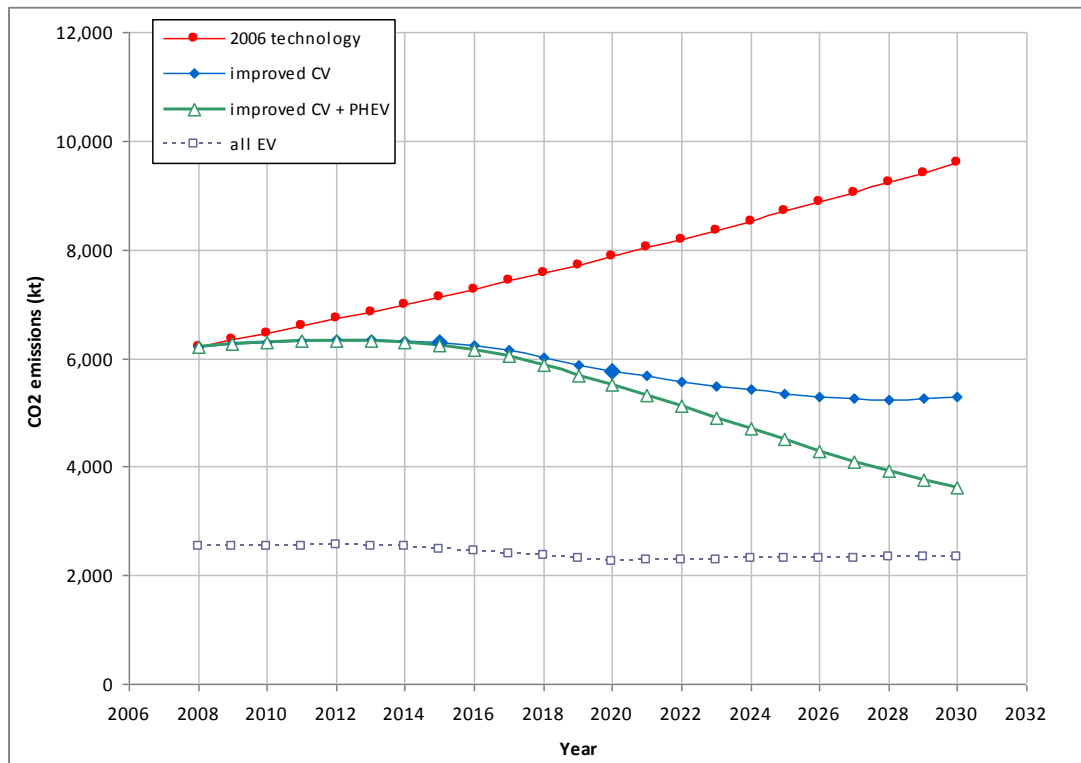


Figure 13 Projected annual CO2 emissions from PC, 2008-2030, PCkm growth 1%.a<sup>-1</sup>



**Figure 14 Projected annual CO2 emissions from PC, 2008-2030, PCKm growth 2%.a<sup>-1</sup>**

The data presented in Figure 13 and Figure 14 is therefore mildly encouraging. Even allowing for an annual increase in PCKm, it seems likely that the proposed reduction in NEDC CO2 emissions of new PC entering the fleet, coupled with the moderately rapid adoption of PHEV, could reduce CO2 emissions from the Irish PC fleet by 700–1,300 kt per annum relative to 2006 values, or 10-20%. Looking farther forward, by 2030 reductions of 2,600-3,200 kt per annum relative to 2006 could be achieved – an impressive 40-50%. It is worth reiterating that these reductions are achieved even in the face of an annual increase in PCKm.

#### Summary and Conclusions:

The analysis of projected energy-intensity and CO2 emissions of the Irish passenger car (PC) fleet presented in this paper can be summarised as follows:

- Electrification of the Irish PC fleet reduces primary energy requirement, and CO<sub>2</sub> emissions, by about 50% for each km travelled in electric mode.

- The planned growth in renewable penetration in the Irish electrical system means that electric vehicles (EV) will maintain this advantage through to 2020 and beyond, notwithstanding the significant improvements in energy efficiency and CO<sub>2</sub> emissions mandated by the EU for new PC.
- Relative to conventional vehicles (CV), EV offer the critical advantage that improvements in PER and CO<sub>2</sub> intensity of the electricity supply system propagate instantaneously throughout the EV fleet; improvements in CV require a decade or more to be fully realized, since they require replacement of the PC fleet.

The clear and significant benefits offered by EV *on a per km basis*, must however be tempered by the following facts:

- Market availability of PHEV will be very limited up to 2011. Subsequent penetration of PHEV into the PC fleet will then require a decade or two, as explained in the body of this paper – assuming that customer demand is strong, and that supply can keep pace with that demand.
- Therefore, PHEV operating in EV mode will probably account for ~10% of PCkm in 2020, increasing to 50% in 2030 (medium scenario). The bulk of the improvement in the PC fleet, at least to 2020, will therefore derive from the implementation of proposals to limit CO<sub>2</sub> emissions from new PC to 130 g.km<sup>-1</sup> by 2015, and 95 g.km<sup>-1</sup> by 2020.
- Furthermore, the analysis in this paper addresses passenger cars (PC) only; PC accounted for “only” 38% of Irish Transport PER in 2006. On its own, therefore, a reduction of 10-20% in PER or CO<sub>2</sub> emissions from the Irish PC fleet yields an improvement of 3.8-7.6% from the Transport sector as a whole.

Notwithstanding these caveats, however, it is clear that electrification of the Irish PC fleet offers the potential for very significant reductions in PER and CO<sub>2</sub> emissions from that sector, particularly beyond 2020. Its impact on the grid is likely to be modest up to that date and, with the advent of smart metering and the potential for vehicle-to-grid (V2G) energy transfers, may enhance grid performance. From an infrastructural perspective, the demands of PHEV are modest. The analysis presented above assumes one charge per day, which many consumers could achieve by plugging in to a regular domestic socket overnight. The presence on-board the vehicle of a range-extending gasoline or diesel-fuelled power plant offers enormous flexibility in the event of grid outages, unexpected or extended trips, etc. The need for on-street charging infrastructure, or for the battery exchange centres proposed by some proponents of pure EV, would therefore be very limited.

This author therefore recommends that Irish policy makers encourage the rapid uptake of PHEV in the Irish PC fleet, with a view to reducing the CO<sub>2</sub> emissions and energy requirement of the sector, whilst simultaneously increasing security of supply, reducing oil- and import-dependence.

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Appendix

Tables (each on a separate sheet)

	<b>Polo</b>	<b>Golf</b>	<b>Passat</b>	<b>Prius</b>	<b>Tiguan</b>	<b>Touareg</b>
<b><i>Drag coefficient</i></b>	0.32	0.31	0.29	0.26	0.37	0.41
<b><i>Frontal area (m<sup>2</sup>)</i></b>	2.04	2.22	2.26	2.15	2.54	2.78
<b><i>mass (kg)</i></b>	1003	1281	1457	1300	1590	2301
<b><i>Rolling resistance coefficient</i></b>	0.01					

**Table 1 Principal characteristics of the vehicles for which drive cycle minimum energy requirement (MER) was calculated**

	<b>Polo</b>	<b>Golf</b>	<b>Passat</b>	<b>Prius</b>	<b>Tiguan</b>	<b>Touareg</b>
<b><i>NEDC</i></b>	88.6	105.5	113.3	99.7	135.4	184.4
<b><i>US06</i></b>	142.8	165.9	174.6	153	215.6	287.3
<b><i>ARTEMIS urban</i></b>	110.3	139.3	157	139.7	173.9	249.1
<b><i>ARTEMIS mway 130</i></b>	147.3	166.4	170.4	148.5	219.3	284.6

**Table 2 Minimum energy requirement (Wh.km<sup>-1</sup>) by vehicle and drive cycle**

"Irish" drive cycle (NEDC + 15%)						
	<b>Polo</b>	<b>Golf</b>	<b>Passat</b>	<b>Prius</b>	<b>Tiguan</b>	<b>Touareg</b>
<b><i>MER (Wh.km<sup>-1</sup>)</i></b>	101.9	121.3	130.3	114.7	155.7	212.1

Table 3 Minimum energy requirement, by vehicle, for "Irish" drive cycle (Wh.km<sup>-1</sup>)

<b>Assumed efficiency values</b>	
<i>Transformer / Inverter</i>	95%
<i>Battery: current input or output</i>	97%
<i>DC machine in Motor mode</i>	90%
<i>Mechanical Transmission</i>	98%
<i>DC machine in Generator mode</i>	85%
<i>Wall socket to wheel efficiency</i>	75%
<i>Wheel to battery regenerative efficiency</i>	77%

Table 4 Component efficiency values assumed for operation in electric mode

"Irish" drive cycle (NEDC + 15%)						
MER (Wh.km <sup>-1</sup> )	Polo	Golf	Passat	Prius	Tiguan	Touareg
<b>0% regeneration</b>	101.9	121.3	130.3	114.7	155.7	212.1
<b>100% regeneration</b>	76.7	88.0	91.2	79.6	115.0	151.2
<b>60% regeneration</b>	86.8	101.3	106.8	93.4	131.3	175.6

Table 5 Minimum energy requirement, by vehicle, for "Irish" drive cycle, with and without regeneration (Wh.km<sup>-1</sup>)

	NEDC	“Irish” drive cycle
<b><i>EV MER (60% regeneration) (Wh.km<sup>-1</sup>)</i></b>	93	107
<b><i>EV WSER at wall socket (Wh.km<sup>-1</sup>)</i></b>	124	140
<b><i>EV PER for electricity supply (Wh.km<sup>-1</sup>)</i></b>	298	337
<b><i>Conventional PC MER (no regeneration) (Wh.km<sup>-1</sup>)</i></b>	113	130
<b><i>Calculated PC PER (Wh.km<sup>-1</sup>)</i></b>	660	750
<b><i>EV PER, relative to PC</i></b>	45%	

Table 6 Energy requirement of PHEV, and conventional PC on NEDC and “Irish” drive cycles

Captions to Illustrations (on a separate sheet) and then

Figure 1 Minimum energy consumption by vehicle and drive cycle

Figure 2 Schematic layout and energy flows for PHEV

Figure 3 Fraction of drive-cycle energy theoretically available for regeneration

Figure 4 Primary energy requirement of PHEV in EV mode, and conventional PC, on the NEDC. Solid symbols denote historic data, others are projected. Dashed lines link values for new vehicles only; solid lines represent fleet averages. New cars are assumed to meet proposed EU CO<sub>2</sub> targets of 130 g.km<sup>-1</sup> and 95 g.km<sup>-1</sup>, in 2015 and 2020 respectively.

Figure 5 Specific CO<sub>2</sub> emissions, and “fossil-fuel efficiency” of Irish electricity supply, as a function of renewable contribution to supply. Solid symbols denote historic data (1995, 2005, 2006, 2007).

Figure 6 CO<sub>2</sub> emissions (g.km<sup>-1</sup>) from conventional gasoline and diesel PC entering the Irish fleet in 2006, compared with emissions from grid-powered EV. For EV, emissions are calculated based on the Irish electricity mix in 2006, and the projected mix in 2010 and 2020.

Figure 7 Average CO<sub>2</sub> intensity of conventional vehicle (CV) fleet and EV fleet on NEDC

Figure 8 Three projections for PHEV sales growth, and consequent PC fleet penetration, with sales commencing in 2011: “rapid” = 50% share of sales by 2018; “moderate” = 50% by 2022; “slow” = 50% by 2026.

Figure 9 Cumulative distribution of trips and PCkm for work trips in Ireland, based on 2006 Census data

Figure 10 Impact of PHEV all-electric range (AER), on percentage of Irish PCkm completed in EV mode, based on author's analysis of 2006 census data

Figure 11 Three projections for PCkm completed in all-electric (EV) mode, depending on growth rate of PHEV sales, and all-electric range (AER) of PHEV sold

Figure 12 Effect of PHEV fleet penetration and AER on projected annual electrical demand

Figure 13 Projected annual CO<sub>2</sub> emissions from PC, 2008-2030, PCkm growth 1%.a<sup>-1</sup>

Figure 14 Projected annual CO<sub>2</sub> emissions from PC, 2008-2030, PCkm growth 2%.a<sup>-1</sup>

Illustrations (each on a separate sheet containing no text).

