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Can EV (electric vehicles) address Ireland's CO_2 emissions from transport?

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ABSTRACT

In the period 1990–2007, CO_2 emissions from Ireland's Transport sector increased by 181%. It has been proposed that a transition to EV (electrically-powered vehicles) – either BEV (battery-powered) or PHEV (plug-in hybrids) – offers the potential for significant reductions in these emissions. However, the benefits of PHEV – and of plug-in vehicles generally – accrue because some fraction of the fossil fuel normally consumed by the vehicle is displaced by electricity extracted from the national grid. The net benefit therefore depends on many factors, including the characteristics of the electricity generation and distribution system, and the proportion of vkm (vehicle-kilometres) completed under electric power.

This paper examines these factors in an Irish context. On the basis of individual vehicles, it is found that electrification yields substantial and immediate reductions in GHG (greenhouse gas) emissions for urban-type driving cycles. For inter-city travel, however, the percentage reduction attainable is much smaller, and the technical difficulty of achieving this capability is much greater. Unless that challenge can be overcome, it is shown, 50–75% of CO_2 emissions from private cars will remain beyond the reach of electrification.

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1. Introduction

Since 1990, Ireland has experienced a surge in growth of the transport sector. The PER (primary energy requirement) of transport increased by 177% between 1990 and 2008 [1], resulting in a corresponding increase in GHG (greenhouse gas) emissions [2]. Although the growth rate was highest for road freight, the largest absolute increase in GHG from the sector was attributable to private cars [1].

Over the same period, the GHG emissions index (g kW^{-1} h^{-1}) of the Irish electricity system has steadily improved, from 896 g CO_2 kW^{-1} h^{-1} in 1990, to 582 g CO_2 kW^{-1} h^{-1} in 2008 [1]. Nonetheless, Ireland needs to further reduce national GHG emissions if it is to meet emissions targets for both the 2008–2012 Kyoto period, and for the EU 2020 deadline [3]. This led the government in 2007 to set ambitious targets for electricity generation from renewable sources [4]. These targets were subsequently increased, and now require that 15% of electricity be derived from renewable sources by 2010, and 40% by 2020 [5]. If met, these targets will reduce CO_2 emissions from the electricity sector to approximately 520 g CO_2 kW^{-1} h^{-1} in 2010, and to ~330 g CO_2 kW^{-1} h^{-1} in 2020 ([6], and Appendix 1).

In this context, electrification of the private car fleet appears tempting, since it might reduce GHG emissions from that source. Moreover, significant collateral benefits would accrue, including reduced oil-dependence, improved air quality in urban areas, and increased sustainability of personal transport. However, the magnitude of the ensuing benefits is dependent not only on the efficiency and Carbon-intensity of the electricity supply system, but also on the efficiency with which EV (electric vehicles) exploit that electricity, and the fraction of PCkm (private car km) completed under all-electric power. The quantification of these latter factors is a primary focus of this paper.

2. EV versus CV (conventional vehicles)

2.1. Advantages of EV

On a TTW (tank-to-wheel), or STW (socket-to-wheel) basis, EVs are generally more efficient than CV (conventional vehicles). Three primary factors drive this increased efficiency:

- greater efficiency of the prime mover - especially at low vehicle speeds and when starting from cold

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Abbreviations: AER, all-electric range; BEV, battery-electric vehicle; CV, conventional vehicle; EU, European Union; EV, electric vehicle; GHG, greenhouse gases; HGV, heavy goods vehicle; ICE, internal combustion engine; ISG, integrated starter-generator; NCT, national car test; NEDC, new European drive cycle; PC, private car; PCkm, private car kilometres; PER, primary energy requirement; PHEV, plug-in hybrid electric vehicle; POWCAR, place-of-work census of anonymised records; STW, socket-to-wheel; TTW, Tank-to-wheel; UDDS, urban dynamometer driving schedule; UNFCCC, United Nations framework convention on climate change; VCA, vehicle certification authority; Vkm, vehicle-kilometres; WSER, wall-socket energy requirement.

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- elimination of engine idling, and
- regenerative braking

The first of these is of fundamental importance. The ICE (internal combustion engine) - petrol or diesel - has a minimum rotational speed at which it can supply shaft power. Even at this minimum speed, the shaft power needed to overcome internal friction in the engine itself is typically of the order of 5 kW, and this requirement increases with rotational speed. At low vehicle speeds, the shaft power required to propel the vehicle may often be much less than that required to overcome engine friction, so that the mechanical efficiency of the engine ranges from 0% (at idle) to perhaps 80% at the optimum operating point.

Furthermore, the shape of the torque-speed curve for ICE requires the use of a gearbox in order to maintain acceptable performance across a broad range of vehicle speeds. The net result is that engine speed generally does not correlate with vehicle speed except under open-road conditions - low vehicle speeds still require moderately high engine speeds, and necessarily, therefore, low engine output torque. Hence, when vehicle speeds are low the mechanical efficiency of ICE is generally very poor.

Overall engine efficiency is a product of its mechanical and thermodynamic efficiencies; the latter is constrained by the Second Law of Thermodynamics, and is typically of the order of 50% for a modern design. Overall engine efficiency therefore ranges from about 40% at the optimum operating point (50% $\times$ 80%), down to 0% at idle.

When starting from cold, the efficiency deficit of the ICE is even greater. Gasoline engines require mixture enrichment to be employed in order to attain acceptable operation, even under mild ambient temperatures. All CV also suffer from the increased viscosity of lubricating oil at low temperatures, which increases the frictional losses in the engine and transmission from a cold start. Although EV may also suffer from this effect, the frictional loads in CV are far greater than in EV (as discussed above), and the penalty of increased oil viscosity is weighted accordingly.

The above characteristics are in marked contrast with those of electric motors, which have high (75–90%) overall efficiencies across most of the speed and load map, and can deliver maximum torque at zero shaft speed (e.g. [7–9]). The latter characteristic obviates the requirement for a gearbox, so that an EV can maintain high mechanical efficiency down to zero road speed. The thermodynamic losses of an EV are associated primarily with the generation and transmission of the electricity that is used to drive the motor. Additional electrical losses occur between the electrical wall socket and the driven wheel but, as will be seen, these losses are generally smaller than the upstream losses. Hence, the overall efficiency of the EV depends on the efficiency of the electrical generation and transmission system, as well as on that of the motor and on-board electrical system.

In addition to the efficiency advantages outlined above, EV benefits from the elimination of engine idling and from the ability to exploit regenerative braking. Because of the efficiency gains associated with their use - particularly in urban-type certification drive cycles-both of these technologies are beginning to appear on modern CV. However, neither can achieve the same level of performance obtained with EV. The “stop-start” technology employed on CV requires driver intervention every time the vehicle stops, and its effectiveness is therefore completely dependent on the degree of driver engagement. A degree of regenerative braking on CV is usually achieved using either the engine alternator or, at greater expense, an ISG (Integrated Starter Generator). Whichever device is employed, the maximum power transfer is heavily constrained by the 14-V electrical system employed on CV, and is limited in practice to about 3–4 kW (200–300 A). These characteristics are in stark contrast to EV, where the regenerative absorption capacity is roughly equal to the electric motor power.

The net result of the above is that, at low vehicle speeds and/or where there is significant potential for regeneration, the TTW efficiency of EV significantly exceeds that of CV. Collateral advantages include a reduction in oil-dependence for the transport sector, zero tailpipe emissions and, given an appropriate electricity generation and transmission system, reduced GHG emissions and energy consumption. It is important to note, however, that inter-city travel normally implies high vehicle speeds, and low potential for regenerative braking; the advantage of EV over CV is therefore significantly reduced in that application.

2.2. Disadvantages of EV

The primary drawbacks of EV derive from the on-board battery packs required to drive the electric motor and to store the regenerative energy recovered during braking. There is an inherent trade-off between energy-density (Wh kg^{-1}) and power-density (W kg^{-1}) for all battery technologies developed to date [10–15]. For EV, high energy flow rates are required to achieve performance comparable to CV, and to maximise the recovery of energy under braking. However, high energy storage capacity is also required to achieve acceptable AER (all-electric range). The cost, size, durability, and thermal management of battery packs impose further stringent limitations on the capability of pure EV [10,12,14].

The amount of time required to recharge the battery constitutes another significant-though rarely discussed-limitation on the applicability of EV. The WSER (wall-socket energy requirement) of an EV depends heavily on the characteristics of the vehicle and of the drive cycle, as shown below. For motorway, or long-distance, travel however, estimates in the literature range from 150 to 250 Wh km^{-1} [11,15–17]. Taking the mean of these values, an inter-city trip of 200 km would require 40 kWh of electrical energy from a wall socket for travel in each direction. If supplied using a standard 3 kW domestic socket, the EV would require over 13 h of charging time to travel each way – compared to about 2 h for the trip itself.

Some BEV, such as the Nissan Leaf, incorporate “rapid-charge” sockets with a power transfer capability up to 50 kW. This author’s discussions with electricity suppliers suggest that they are very reluctant to exceed this rating for charging points that will be operated by the general public, so it is unlikely that charging rates above this value will become widespread. However, even the use of a 50 kW, dedicated EV charging point would require almost an hour of charging time in each direction-assuming that a charging point is available on demand. In practice, with recharge periods of this duration, the availability of charging points might quickly constitute a significant constraint.

The charging requirement is exacerbated by the fact that battery storage is expensive, heavy, and bulky (e.g. [10]), so that the range achievable under all-electric operation is very limited. The recently-announced Nissan Leaf, a pure BEV, has a battery storage capacity of 24 kWh, of which 16 kWh is likely to be usable. Whereas this might be adequate for the claimed 100 miles (160 km) of AER on an urban drive cycle such as the US UDDS, the AER is likely to fall to about 60 miles (100 km) on the motorway-style drive cycle associated with inter-city travel-see for instance Ref. [17]. Nissan itself is quoted [18] as stating that the range could drop as low as 77 km (48 miles) if the car is driven hard on a motorway with the air-conditioning on. On that basis the vehicle will need to stop at least once to recharge during each 200 km leg of the proposed trip, as well as at each end. Even assuming the availability of a 50 kW charger at an appropriate location, this will add at least 30 min to each 2-h trip; in practice the time penalty is likely to be considerably longer. Consequently, the AER of mass-market, light-duty vehicles such as PC (private cars) is heavily constrained, and the use

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