Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 105 (2017) 2983 – 2988

Energy Procedia

The 8th International Conference on Applied Energy – ICAE2016

Can Electric Vehicles Deliver Energy and Carbon Reductions?

Patrick Moriarty[a*], Stephen Jia Wang[b]

[a,b]*Department of Design, Monash University, Caulfield East 3145, Australia*

[a,b]*International Tangible Interaction Design Lab, Monash University, Caulfield East 3145, Australia*

Abstract

Electric vehicles (EVs) are often thought to be an important means for reducing both the greenhouse gas emissions and energy consumption of global transport, particularly for road passenger transport. They are potentially more fuel efficient than comparable internal combustion engine vehicles (ICEVs), particularly in urban areas, because of regenerative braking. It is well-recognised that the energy efficiency of EVs decreases with the range the batteries must provide (because of rising battery mass), and that greenhouse gas comparisons with ICEVs depend on the grid electricity source. However, this paper argues that comparing EVs and ICEVs is much more complex than generally recognised. Uncertainties occur in both primary energy use and greenhouse gas emission calculations. Further, it may not be legitimate to evaluate these terms on a simple vehicle-km basis, because of spillover effects.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.

Keywords: Carbon emissions; electric vehicles; energy efficiency; energy storage; spillover effects

1. Introduction

Global transport is both a major consumer of world oil output, as well as a leading source of greenhouse gas (GHG) emissions, particularly from carbon dioxide (CO_2). Reducing both energy use and GHG emissions from transport could thus play an important part in solving both the global fossil fuel (particularly oil) depletion and climate change challenges the world increasingly faces. Electric vehicles (EVs), here taken to include full battery EVs as well as plug-in hybrid EVs, are often regarded as an important means of solving both problems [1]. Additionally, they are seen as helping ameliorate urban air

* Corresponding author. Tel.: 61 3 9903 2584; fax: +61 3 9903 1440
E-mail address: patrick.moriarty@monash.edu.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.
doi:10.1016/j.egypro.2017.03.713

pollution. Other researchers [e.g. 2-4] have argued that significant barriers to EV adoption remain because of a variety of social and technical barriers.

Ma et al [5] compared the GHG emissions from EVs and internal combustion engine vehicles (ICEVs) on a full life cycle basis for Californian and UK grids. They found, as expected, that EVs performed comparatively better in California than in the UK, because of the less fossil fuel-intensive grid. They further found that EV performance improved for low-speed urban driving conditions, and that the GHG costs of vehicle manufacture were higher than for ICEV manufacture, mainly because of battery manufacture. Onat et al [1] did an energy and GHG analysis for each state in the US for ICEVs, EVs and hybrid EVs. They found that both EVs and hybrids had lower full life cycle energy consumption than ICEVs for the US overall, and also lower carbon emissions. However, hybrids were superion to EVs for energy consumption in nearly all states. Finally, Hawkins et al [6] summarised their findings as follows: 'We find that EVs powered by the present European electricity mix offer a 10% to 24% decrease in global warming potential (GWP) relative to conventional diesel or gasoline vehicles assuming lifetimes of 150,000 km. However, EVs exhibit the potential for significant increases in human toxicity, freshwater eco-toxicity, freshwater eutrophication, and metal depletion impacts, largely emanating from the vehicle supply chain. Results are sensitive to assumptions regarding electricity source, use phase energy consumption, vehicle lifetime, and battery replacement schedules.'

Nomenclature

CH_4	methane
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
EV	electric vehicle
GHG	greenhouse gas
ICEV	internal combustion engine vehicle
IEA	International Energy Agency
N_2O	nitrous oxide
PEB	pro-environmental behavior
PV	photovoltaic cell
RE	renewable energy
V2G	vehicle to grid

This paper re-examines the extent to which EVs can effectively address the global climate change and fossil fuel depletion problems. Because only 4.4% of electricity generated worldwide in 2013 was from oil [7], EVs can undeniably help delay the onset of 'peak oil'. But this paper argues in the following three sections that it is not possible to say definitively whether a major shift to EVs would help save either energy or GHGs compared with continuation of conventional petrol or diesel fuelled vehicles.

2. Energy efficiency comparisons

Comparing the energy efficiency of different internal combustion engine vehicles (ICEVs) is easy; just compare vehicle-km for each vehicle per litre of petrol used, for example. But for EV vs ICEV comparisons, both petrol and electricity must be converted to primary energy terms—for instance crude oil for ICEVs and coal for electricity from coal-fired electric plants.

But a difficulty arises when converting electricity to primary energy for different non-fossil fuels. For thermal electricity production in nuclear or geothermal power plants, primary energy is always calculated from the heat energy used to generate the electricity, just as for fossil fuel power stations. For non-thermal renewable electricity, such as that produced by hydro plants or wind turbines, different authorities use different conversion methods [8]. The International Energy Agency (IEA) [7] convert hydro, photovoltaic cell (PV), and wind electricity on a 1:1 basis. In contrast, BP converts hydroelectricity to primary energy in the same manner as for nuclear electricity 'on the basis of thermal equivalence electricity in a thermal power station assuming 38% conversion efficiency in a modern thermal power station' [9].

It follows that the primary energy efficiency calculated for a given EV will vary greatly depending on the source of the non-fossil energy. In a grid using 100% nuclear power, the efficiency would be identical to that of a grid using 100% hydroelectricity if calculated by the BP method, but much lower if the IEA method was used. Clearly, this is an unsatisfactory result. It also makes ICEV vs EV energy efficiency calculations arbitrary for grids using significant amounts of primary renewable energy (RE) electricity. The problem can only get worse if, as expected, wind, hydro, and especially PV electricity, supply ever higher percentages of global electricity.

A further complication arises if there is a need for energy storage. The share of nuclear electricity is falling, and even the International Atomic Energy Association does not forecast its share to increase much, if at all [10]. Although carbon capture and storage is relied on heavily in the Intergovernmental Panel on Climate Change scenarios for climate mitigation, it is a largely unproven technology [11], and further, has high energy costs [12] and long lead times for implementation.

It follows that RE will need to assume a major role in long-term climate mitigation [13]. However, the RE sources with the most potential, wind and solar electricity [14], are both intermittent sources, and so will require some form of energy storage if electricity supply is to match demand at all times. At present, electricity production from these sources is small enough [9] to be assimilated into existing grids (where nearly all power comes from fossil fuel, hydro, and nuclear plants), but this will have to change. Energy storage, perhaps using energy carriers such as hydrogen or methanol, will significantly decrease the net electricity available from a given gross wind and solar energy output. The primary energy costs for EVs powered from these intermittent sources will therefore rise.

One suggested way to reduce the need for energy storage by electricity utilities or residences is to use 'vehicle to grid' (V2G) storage. With V2G storage, EVs would be plugged into the electricity grid, and would store energy in their battery packs, and sell such stored electricity to the grid when electricity demand exceeds generated supply [15]. But such an approach would conflict with the proposal for extensive car-sharing, which would greatly reduce the number of vehicles owned. At present, vehicles are on the road for only 4-5% of the time [3]. Inevitably, the shared vehicles would now be used more intensively (i.e. driven more km annually), so that their parking time would also be reduced. The opportunities for daytime charging and grid energy storage would thus be reduced. Night-time charging of batteries would be needed, but, if solar energy is to be the dominant energy source in future, night-time is when the grid would need to draw power from vehicle batteries, not supply it.

3. Greenhouse gas emissions comparisons

The problem identified in the previous section can be avoided if ICEV vs EV comparisons are done on the basis of CO_2, or more generally, GHG emissions, usually expressed as equivalent CO_2 (CO_2-eq). But then a new problem emerges: in nearly all published comparisons, non-fossil fuel electricity (RE and nuclear), it is assumed that these sources generate zero GHG emissions, that they are 'zero carbon' sources.

But this is far from the case. While it is true that these sources *directly* generate negligible GHGs, such is not the case for their indirect emissions. Hydroelectricity is by far the largest source of RE electricity, and much of the remaining untapped potential lies in the tropical regions of Africa, Latin America and Asia [11, 16]. If reservoirs behind tropical dams contain decaying vegetable matter (such as happens if forest is submerged) significant emissions of both CO_2 and methane (CH_4) can occur. The CO_2 arises from aerobic decay; the CH_4, a potent GHG, from anaerobic decay. During the early years of operation, the CO_2-equivalent emissions can rival that of a natural gas powered plant with the same electricity output [17]. Geothermal plants can likewise emit some GHGs [11]. In both cases, it is important to subtract baseline emissions (emissions before the electricity plant was built) to obtain a fairer picture of emissions.

For other RE sources, GHG emissions arise from the inputs for constructing RE plants, or in the case of bioenergy, for growing the biomass. Since fossil fuels still account for 86.3% of all commercial energy [9], most energy inputs for constructing and maintaining the renewable energy devices are still derived from fossil fuels. Significant nitrogenous fertilizer inputs will be needed for improving the annual yield per hectare of bioenergy, particularly on the marginal soils that will remain after global food and fibre needs are satisfied. But fertilizers produce nitrous oxide (N_2O), a potent and long-lived GHG [18]. Crutzen et al [19] have even controversially argued that because of N_2O release from fertilized soils, biomass fuels could produce similar or even higher levels of CO_2-eq than fossil fuels.

It might be thought that for a country such as Norway, with nearly 100% of electricity generated from hydro, replacement of existing oil-fuelled road vehicles by EVs would lead to large reductions in transport GHGs. But it must be remembered that Norway is part of a wider European grid, and exports surplus hydroelectricity to other countries. It is probable that the more hydro Norway consumes, the more electricity will need to be generated from fossil fuels in other parts of the European grid to replace Norwegian hydro imports.

4. Spillover effects for EVs

So far the comparisons have been based on comparisons of primary energy use and GHG emissions per vehicle-km for EVs and ICEVs. However, such comparisons will not be valid if *spillover effects* occur. Positive spillover occurs if 'promotion of one pro-environmental behavior (PEB) raises the likelihood that individuals will adopt other PEBs' [20]. Negative spillover occurs when introduction of a specific PEB (such as waste recycling) leads to lower adoption of other PEBs by individuals. Negative spillovers are related to other concepts such as 'energy rebound' and 'moral licensing' [21].

Klöckner et al [22] specifically examined such effects for EVs in Norway. EVs are selling well in Norway, given that various vehicle taxes are lower or waived, as also are road tolls and car parking costs. They found that if households have only an EV, they do drive it less than conventional car owners. However, most household purchases of EVs are as an addition to the household fleet, not as replacement vehicles. These EV-owning households drove their EVs more than expected, most likely because of the subsidies already mentioned for EVs. Hence a negative spillover appears to be at work, which renders direct comparison of energy or CO_2-eq per vehicle-km for EVs and ICEVs problematic.

5. Discussion and conclusions

EVs are definitely superior to ICEVs for reducing transport oil use and local air pollution. Given that electricity costs are also much lower than petrol costs per vehicle-km, EVs would also have lower operating costs, particularly in Europe, with its high petroleum-based fuel costs [7]. Electricity grids can (and usually do) operate on a variety of fuels, easing the transition to EVs running on entirely non-fossil electricity. As expected, the literature is equivocal on the primary energy and GHG benefits of EVs. If a kilometre range matching ICEVs is needed, then the increased battery mass will both lower EV energy efficiency, and raise GHG emissions. GHG emissions will also depend on the mix of fuels used to power the grid. Both energy and GHG comparisons will also be sensitive to the assumed lifetime vehicle-km and the driving cycle.

This paper has raised several other questions not usually addressed in the many studies examining the relative energy use and GHG emissions of EVs vs ICEVs. First, energy efficiency comparisons are complicated by the conflicting methods used for primary electricity sources such as hydro, solar, or wind. This problem can only become more serious if wind and solar electricity dominate future energy supply [23]. The energy costs of storing these intermittent energy sources are a further complication. Second, for GHG comparisons, the direct emissions of some RE sources add another source of uncertainty. Further, if increased use of EVs in a RE-rich country like Norway leads to lower RE electricity exports, then the system-wide GHG benefits of EVs must be lowered accordingly. Third, a new, apparently 'green' technology like EVs generate spillover effects, further complicating comparisons.

Overall, the conclusion must be that the energy and GHG benefits of EV introduction are less than usually assumed. Only when inter-connected grids are dominated by RE electricity sources will it be safe to claim EV superiority.

References

[1] Onat NC, Kucukvar M, Tatari O. Conventional, hybrid, plug-in hybrid or electric vehicles? State-based comparative carbon and energy footprint analysis in the United States. *Applied Energy* 2015;**150**:36–49.

[2] Steinhilber S, Wells P, Thankappan S. Socio-technical inertia: Understanding the barriers to electric vehicles. *Energy Policy* 2013;**60**:531–539

[3] Sovacool BK, Hirsh RF. Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition. *Energy Policy* 2009;**37**:1095–1103.

[4] Moriarty P, Wang SJ, Eco-efficiency indicators for urban transport*, Journal of Sustainable Development of Energy, Water and Environment Systems* 2015; **3(2)**: 183-195.

[5] Ma H, Balthasar F, Tait N, Riera-Palou X, Harrison A. A new comparison between the life cycle greenhouse gas emissions of battery electric vehicles and internal combustion vehicles. *Energy Policy* 2012;**44**:160–173.

[6] Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH. Comparative environmental life cycle assessment of conventional and electric vehicles. *J Ind Ecol* 2013;**17**:53–64.

[7] International Energy Agency (IEA), *Key world energy statistics 2015*. Paris: IEA/OECD; 2015.

[8] Moriarty P, Honnery D. A hydrogen standard for energy accounting*? Int. J Hydrogen Energy* 2010;**35**:12374-12380.

[9] BP. *BP statistical review of world energy 2016*. London: BP; 2016.

[10] International Atomic Energy Association (IAEA) *Energy, electricity and nuclear power estimates for the period up to 2050*. Vienna: IAEA; 2012.

[11] Moriarty P, Honnery D. *Rise and fall of the carbon civilisation*. London: Springer; 2011.

[12] Anderson K. Duality in climate science, *Nature Geosci* 2015;**8**:898–900.

[13] Moriarty P, Wang SJ, Assessing global renewable energy forecasts, *Energy Procedia* 2015; **75**: 2523-2528.

[14] Moriarty P, Honnery D. What is the global potential for renewable energy? *Renew & Sustain Energy Rev* 2012;**16**:244–52.

[15] Turton H, Moura F. Vehicle-to-grid systems for sustainable development: An integrated energy analysis. *Technol Forecasting & Soc Change* 2008;**75**:1091–1108.

[16] World Energy Council (WEC). *World energy resources: 2013 survey*. London: WEC; 2013.

[17] Fearnside PM. (2004) Greenhouse gas emissions from hydroelectric dams: controversies provide a springboard for rethinking a supposedly clean energy source. *Clim Chang* 2004;**66(2–1)**:1–8. doi:10.1023/B:CLIM. 0000043174.02841.23

[18] Intergovernmental Panel on Climate Change (IPCC). *Climate change 2014: Mitigation of climate change*. Cambridge UK and New York, USA: CUP; 2014.

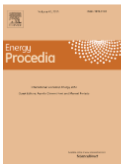
[19] Crutzen PJ, Mosier AR, Smith KA, Winiwarter W. N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmos Chem Phys* 2008;**8**:389–395.

[20] Truelove HB, Carrico AR, Weber EU, Raimi KT, Vandenbergh MP. Positive and negative spillover of pro-environmental behavior: An integrative review and theoretical framework. *Glob Environ Change* 2014;**29**:127–138.

[21] Merritt AC, Effron DA, Monin B (2010) Moral self-licensing: When being good frees us to be bad. *Soc & Person Psych Compass* 2010;**4/5**:344–357.

[22] Klöckner CA, Nayum A, Mehmetoglu M. Positive and negative spillover effects from electric car purchase to car use. *Transp Res D* 2013;**21**:32–38.

[23] Moriarty P, Honnery D. Can renewable energy power the future? *Energy Policy* 2016;**93**:3-7.



Biography

Patrick Moriarty (research: energy, transport, global futures) is Adjunct Associate Professor; Stephen Jia Wang (research: Tangible Interaction Design, behavioral changes for sustainability) is Senior Lecturer, Director of ITIDLab and Program Director in Interaction Design, both in the Department of Design, Monash University, Australia.