Imperial College London

Techno-economic and behavioural analysis of BEV, FCEV and FCHEVs in a future UK sustainable road transport system

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Introduction

- Road transport ~20% CO_2 emissions
  - Regulation and other emissions
  - Climate Change
- Dependent upon oil
  - Peak oil
  - Energy security
- Alternatives
  - Electricity
  - Hydrogen
  - Biofuels & other liquid fuels

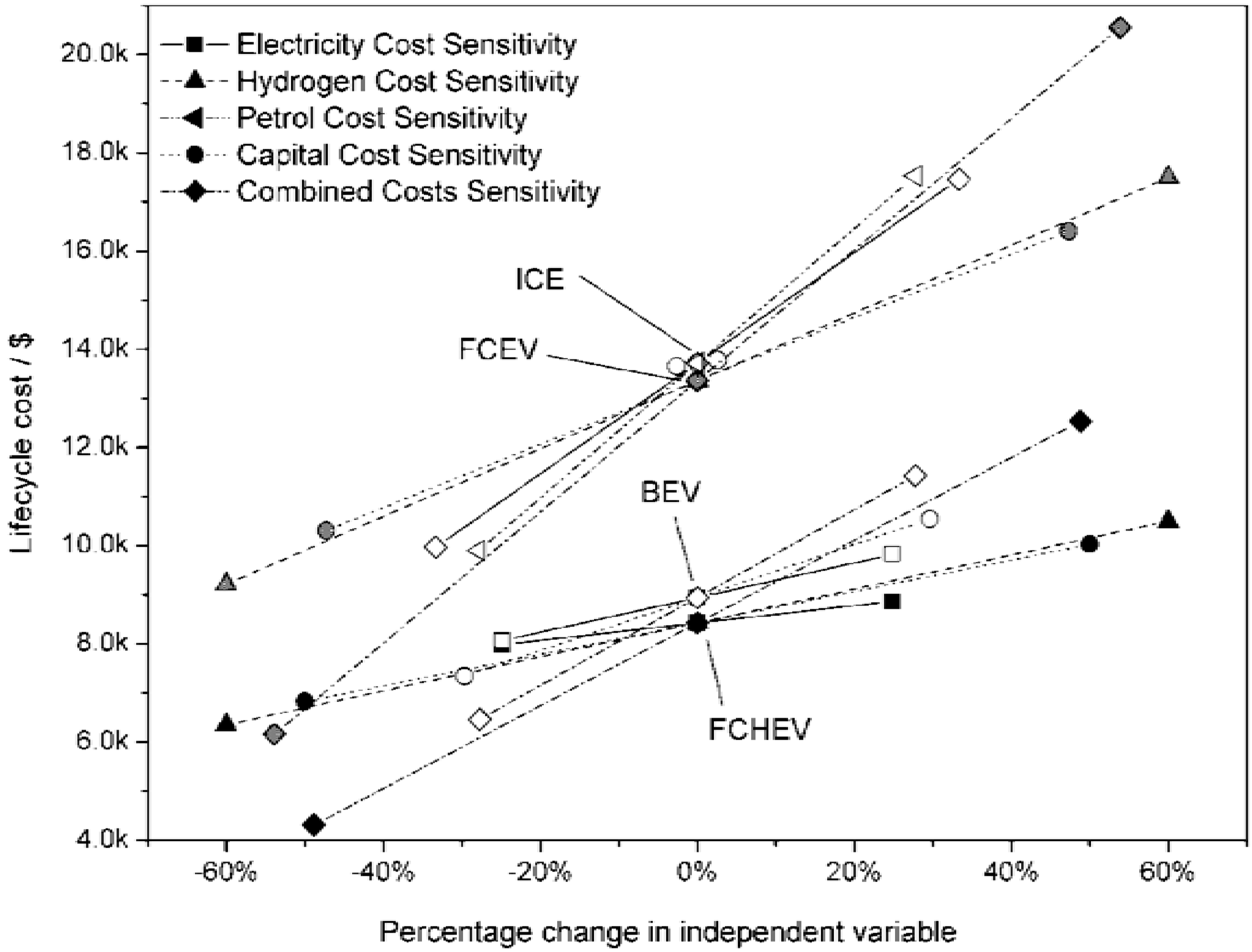
Hydrogen & Electricity

- Synergistic not antagonistic.
- Assumption: Hybrid configurations cheaper!
- Question: Is this true and what is optimum hybrid configuration?

	Hydrogen & Fuel Cells	Electricity & Batteries
Fuel lifecycle efficiency	Good for conventional Bad for electrolysis	Good for conventional V. Good for renewables
Technology cost	Costly for peak power Okay for average power	Cheap for peak and average power
Range	Independent of device	Dependent and Costly
Cost of fuel	Large variability	Cheap

Answer Part A.

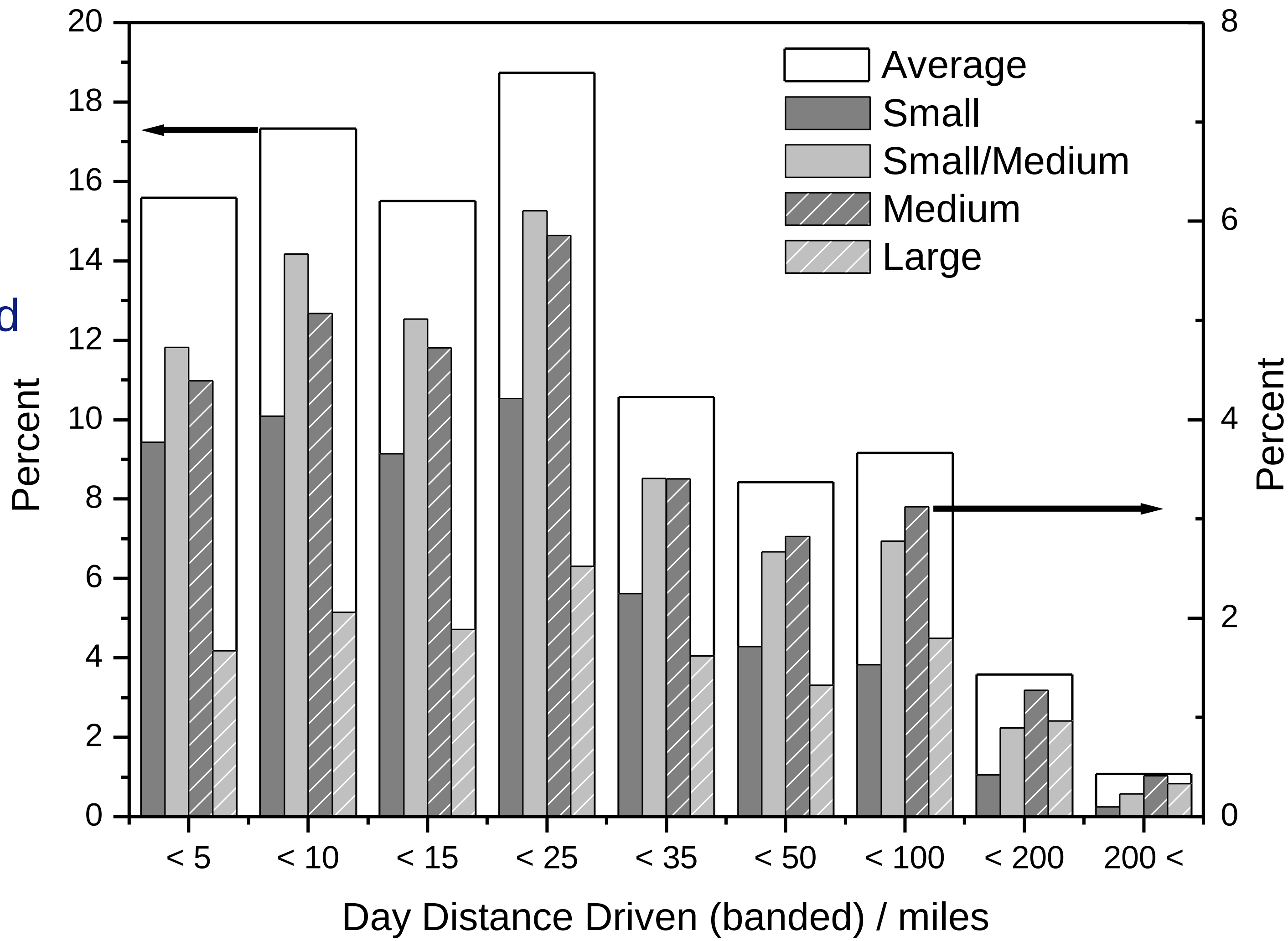
- Yes, hybrid configurations are cheaper.
- Assumed
  - 20 kW fuel cell
  - 6 kWh battery
  - 50:50 usage
- Question Part B.
- What is optimum?



Offer G.J. et al., Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. Energy Policy (2009), doi:10.1016/j.enpol.2009.08.040

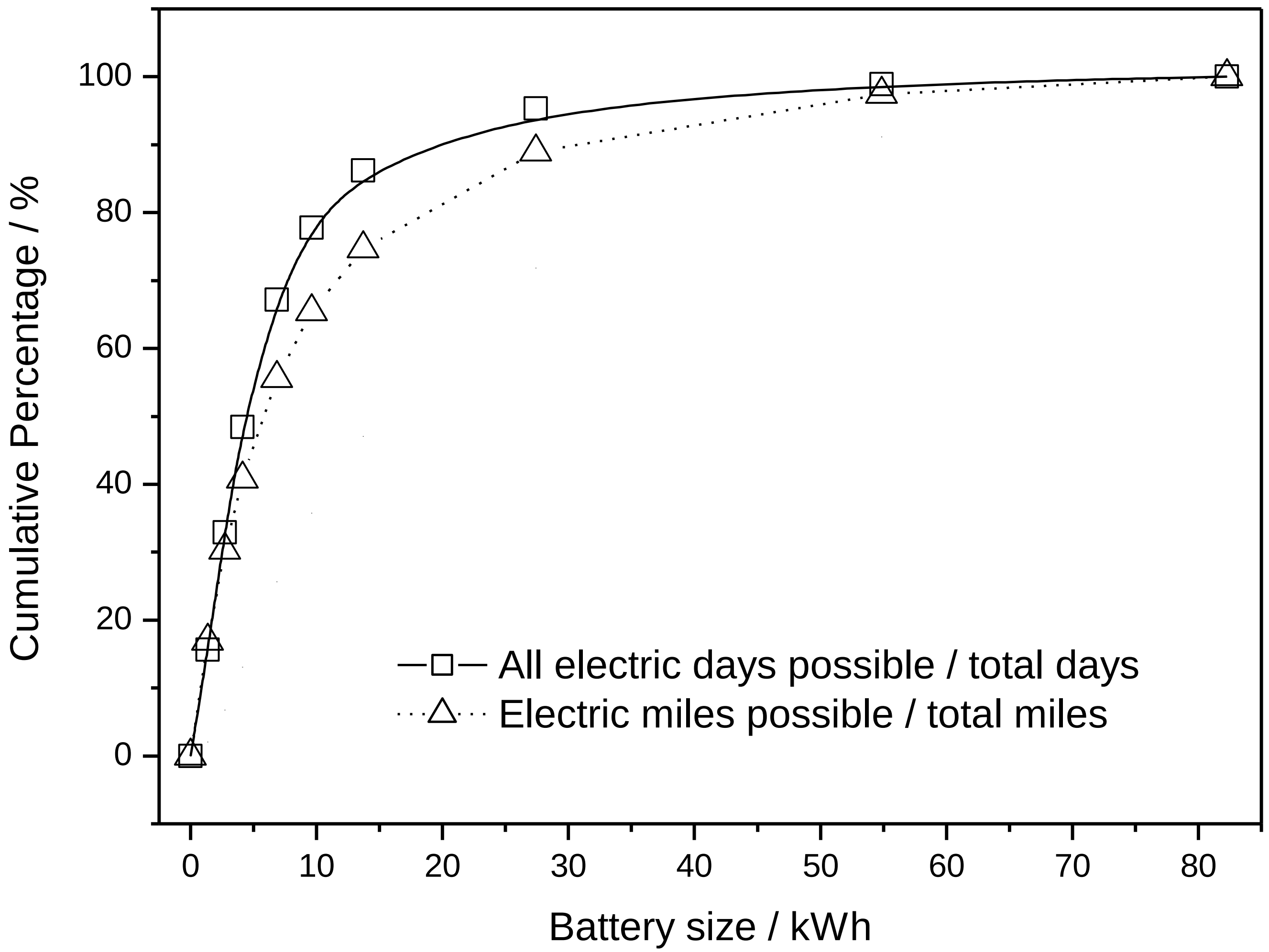
Driving behavioural analysis

- UK National Travel Survey Data
- Nationwide distribution
  - Aggregated &
  - Different car types



Hybrid battery size generation

- For baseline vehicle
  - NTS = Medium
  - VED = Multi-purpose
- Assumptions
  - 100% capacity useable
  - Single overnight charge



Capital cost assumptions

Powertrain component	Minimum	Average = baseline	Maximum
20 kW_e fuel cell	$1,225 [#]	$1,866 [#]	$2,508 [#]
80 kW_e fuel cell	$4,900 *	$7,465 *	$10,030 *
Battery price / kWh	$200 [φ]	$250 [φ]	$300 [φ]
Electric machine	$1,200 *	$1,615 *	$2,030 *
Hydrogen storage	$900 *	$1,450 *	$2,000 *
Conventional (ICE)	$2,400 *	$2,465 *	$2,530 *

* Taken from IEA Energy Technology Essentials: Fuel Cells 2007

[#] Adapted from IEA Energy Technology Essentials: Fuel Cells 2007

[φ] Taken from Investigation into the Scope for the Transport Sector to Switch to Electric Vehicles and Plug-in Hybrid Vehicles, BERR and DfT 2008.

Fuel cost and CO_2 emission assumptions

Fuel	Minimum	Average = baseline	Maximum	Miles GJ^{-1}	Typical units for baseline
Gasoline	\$19 GJ^{-1}	\$28.5 GJ^{-1}	\$38 GJ^{-1}	253	40 mpg *
Hydrogen φ	\$14 GJ^{-1}	\$35 GJ^{-1}	\$56 GJ^{-1}	506 #	72 miles kg^{-1}
Electricity φ	\$27 GJ^{-1}	\$36 GJ^{-1}	\$45 GJ^{-1}	1,013 #	3.65 miles kWh^{-1}

* Powertrain efficiency of ICE engine matched to VED data for multi-purpose vehicle in 2004

\# Powertrain efficiencies assumed to be x2 and x4 more efficient for hydrogen fuel cell and battery electric vehicles respectively [Ref: Granovskii, M., I. Dincer, and M.A. Rosen,. Journal of Power Sources, 2006. 159(2): p. 1186-1193]

φ Energy cost assumptions are based upon the UKERC review of electricity costs in 2007 by P. Heptonstall, and the IEA Energy Technology Essentials: Hydrogen Production and Distribution. 2007.

Baseline vehicle	Petrol	Hydrogen *	Electricity (2008) #
CO_2 emissions / $gCO_2\ MJ^{-1}$	77.6	62.2	150
Fuel consumption / MJ $mile^{-1}$	3.95	1.98	0.99
Emissions / $gCO_2\ km^{-1}$	192	77	93

* Hydrogen carbon dioxide emissions are assumed to be 62.2 $gCO_2\ MJ^{-1}$ based upon a value of 8.9 $kgCO_2\ kgH_2^{-1}$ for steam reforming natural gas and a calorific value of 143 MJ kgH_2^{-1}

\# Electricity carbon dioxide emissions are assumed to be 150 $gCO_2\ MJ^{-1}$ based upon the 2008 UK average electricity emissions of 540 $gCO_2\ kWh^{-1}$ (Defra) which included 5.5% of electricity generation from renewables.

Other assumptions

	Minimum	Average = baseline	Maximum
Lifetime mileage #	n/a	109,000	n/a
CO_2 cost per Tonne *	$222	$500	$778
Reduction in electricity CO_2 emissions per kWh	20%	50%	80%
Charging	n/a	Single overnight	n/a

* Carbon costs were based around the estimated social costs of carbon dioxide emissions in the Stern Review of $500 by 2030, and the upper estimate from effective cost of the 95 Euros per gCO_2 km^{-1} in 2020

Lifetime mileage was calculated from the average mileage driven in the UK in 2008 of 8,265 miles and the average age of "scrappage" for a UK car in 2007 of 13.2 years

φ Electricity emissions reductions are varied between 20% and 80% considering the high degree of uncertainty in this area. The UK target for 2030 is ostensibly to decarbonise electricity generation entirely, with a target of 40% by 2020

Vehicle size and type assumptions

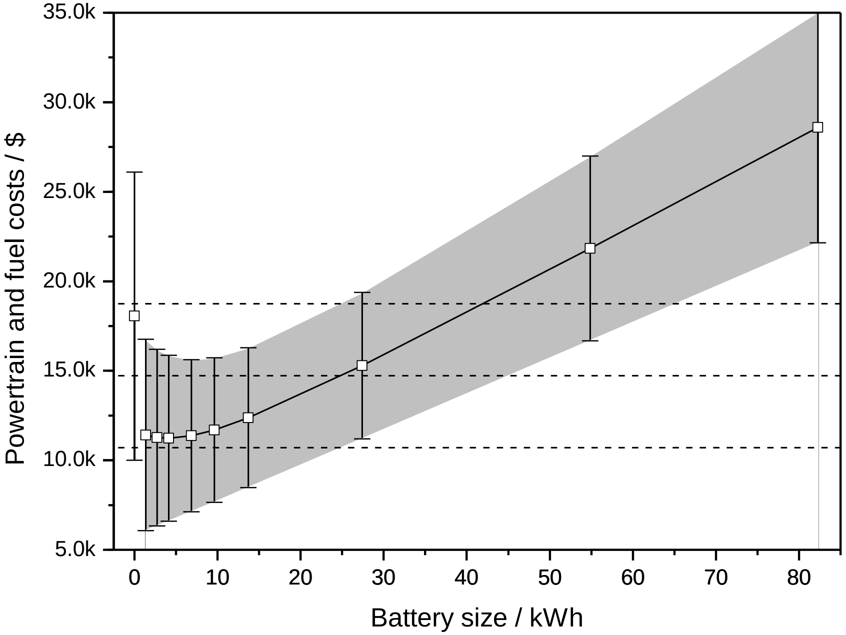
- Not straightforward
- Matched emissions from VED market segments
- Assuming
  - 2x efficient for FCEV
  - and 4x for BEV
- And, average of all types of driving

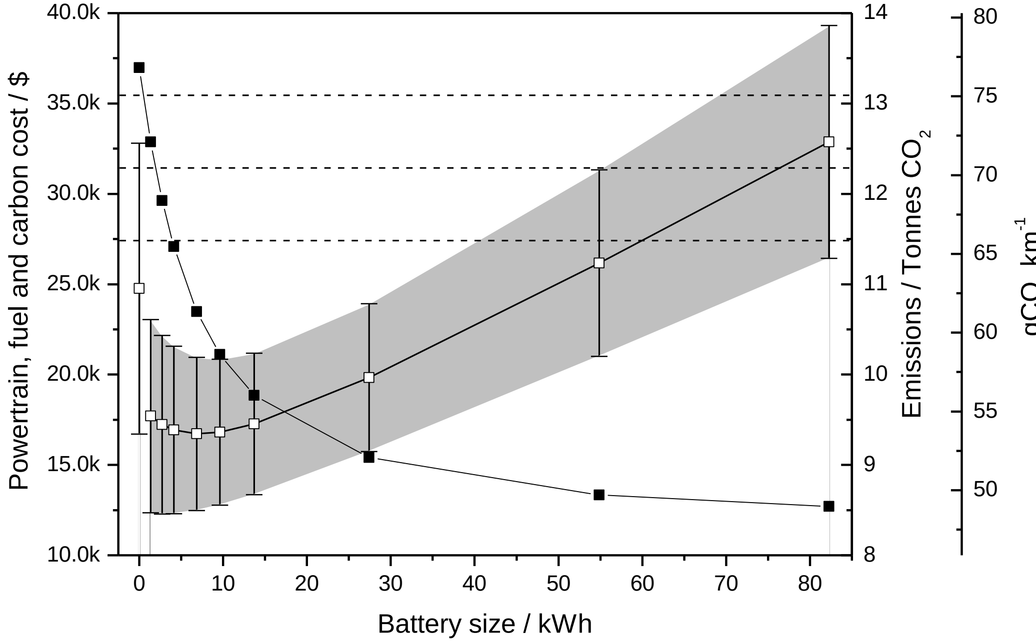
UK NTS types	Small	Small/ Med	Med	Large
VED market segments	Super mini	Lower medium	Multi-purpose	Luxury
Equivalent ICE mpg	51	45	40	28
FCEV fuel cell size / kW	62.7	71	80	114
FCHEV fuel cell size / kW	15.7*	17.8*[1]	20*	29*
H_2 MJ $mile^{-1}$	1.55	1.76	1.98	2.82
H_2 mile kg^{-1}	92	81	72	51
E MJ $mile^{-1}$	0.77	0.88	0.99	1.41
E mile kWh^{-1}	4.70	4.11	3.65	2.56

Calculated from power needed to maintain average speed of 70 mph on motorway

Carbon costs, effect on ICE comparison

- Baseline = all assumptions average
  - Results shown on left exclude carbon
  - Results shown on right include fixed carbon cost (average = $500)
  - All other assumptions fixed unless otherwise stated (yellow)



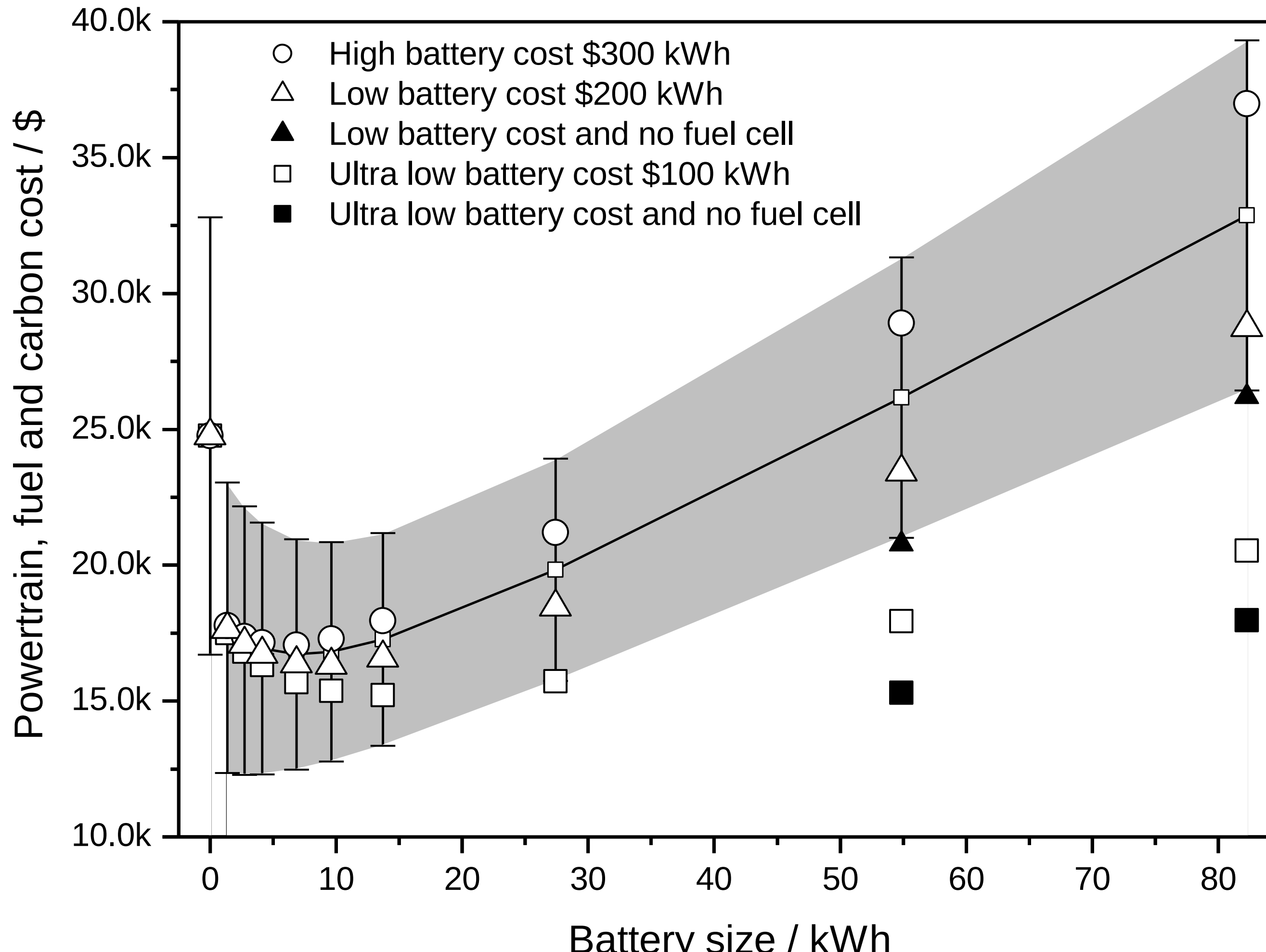


Shaded error bars X-axis Fixed assumptions

$$Cost = f\Big(\big(C_{H_2}.C_E.C_{FF}\big)\big(C_{Batt}.C_{FC}.C_{ICE}\big)\big(B_{Size}\big)\big(FC_{Size}\big).\big(C_{CO_2}.f\left(E_{Gen}\right)\big)\big(f\left(behaviour\right).f\left(vehicle\right)\big)\Big)$$

Battery costs, dominates costs

- Dominate costs of FCHEV
  - Highly sensitive for large battery size
- Diminishing returns beyond ~10 kWh
- If range not a concern a BEV may be possible



$$Cost = f\left(\left(C_{H_2}.C_E.C_{FF}\right)\left(C_{Batt}.C_{FC}.C_{ICE}\right)\left(B_{Size}.FC_{Size}\right).\left(C_{CO_2}.f\left(E_{Gen}\right)\right).\left(f\left(behaviour\right).f\left(vehicle\right)\right)\right)$$

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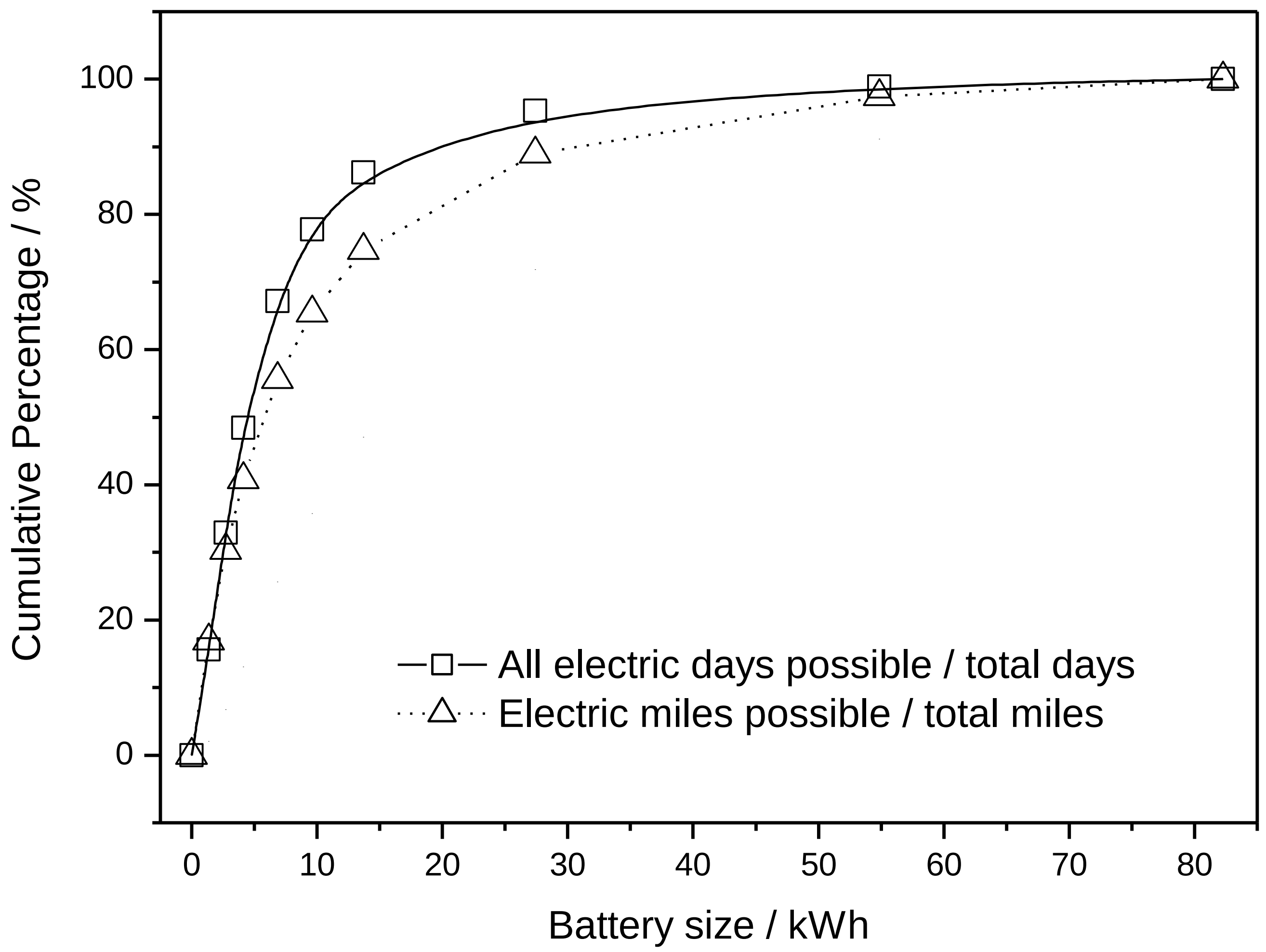
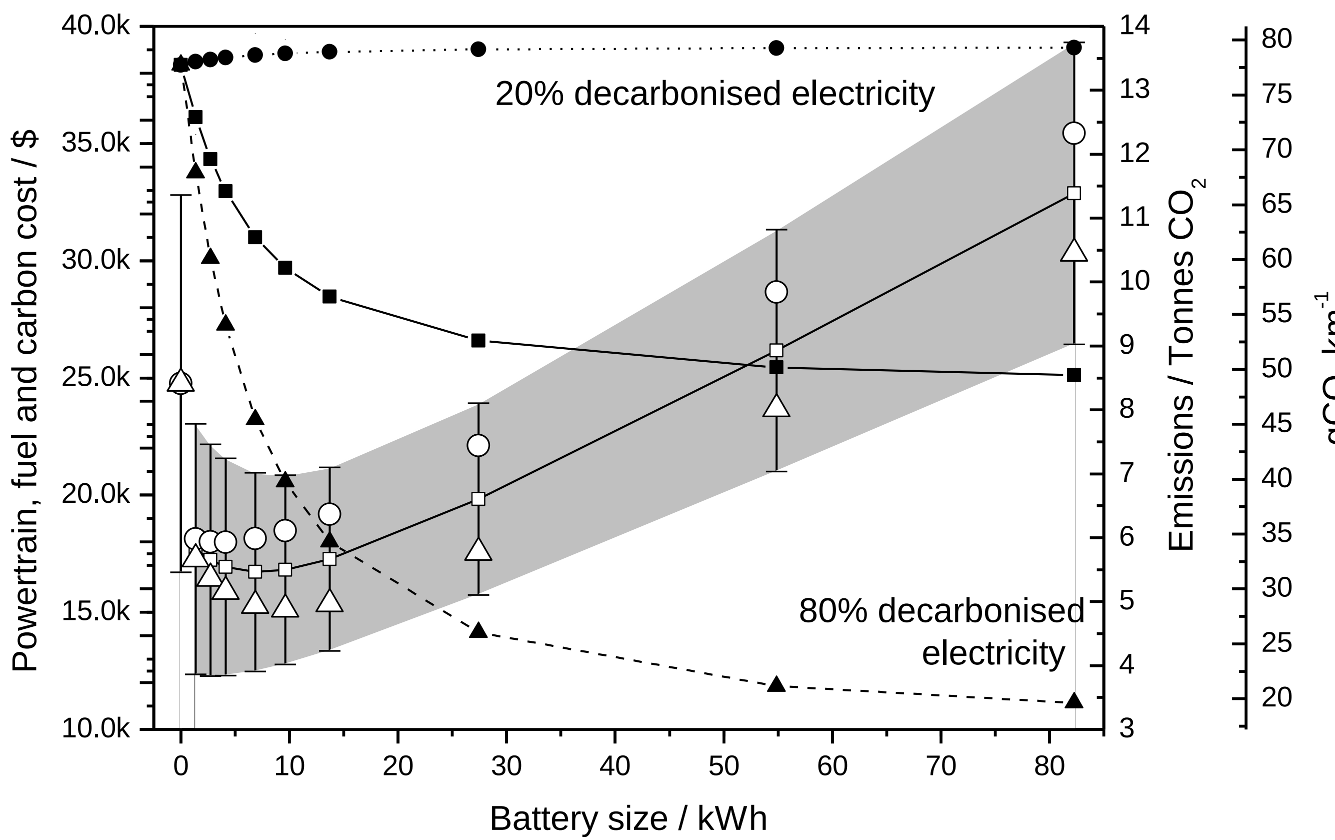


Decarbonising electricity generation, necessary

- Dominates emissions
  - Favours larger battery size
  - Only if carbon is costed
- Hydrogen production
  - Assumed steam reformed methane
  - Different methods of hydrogen production may balance this effect

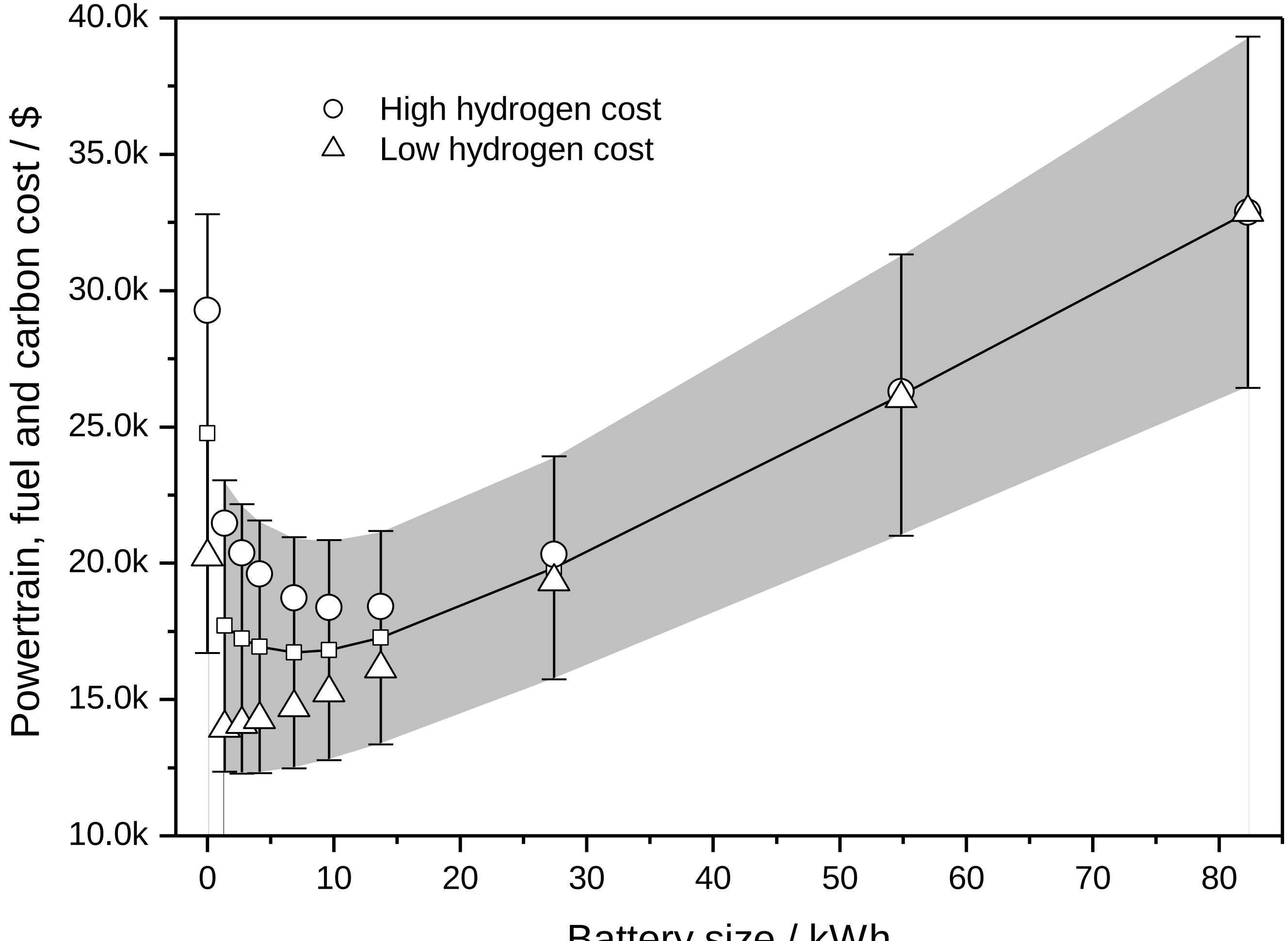


Note: Both electricity and hydrogen offer ~50% reduction in emissions today!

$$Cost = f\left((C_{H_2}.C_E.C_{FF})(C_{Batt}.C_{FC}.C_{ICE})(B_{Size}.FC_{Size}).(C_{CO_2}.f(E_{Gen})).(f(behaviour).f(vehicle))\right)$$

Hydrogen costs, dominates for small battery size

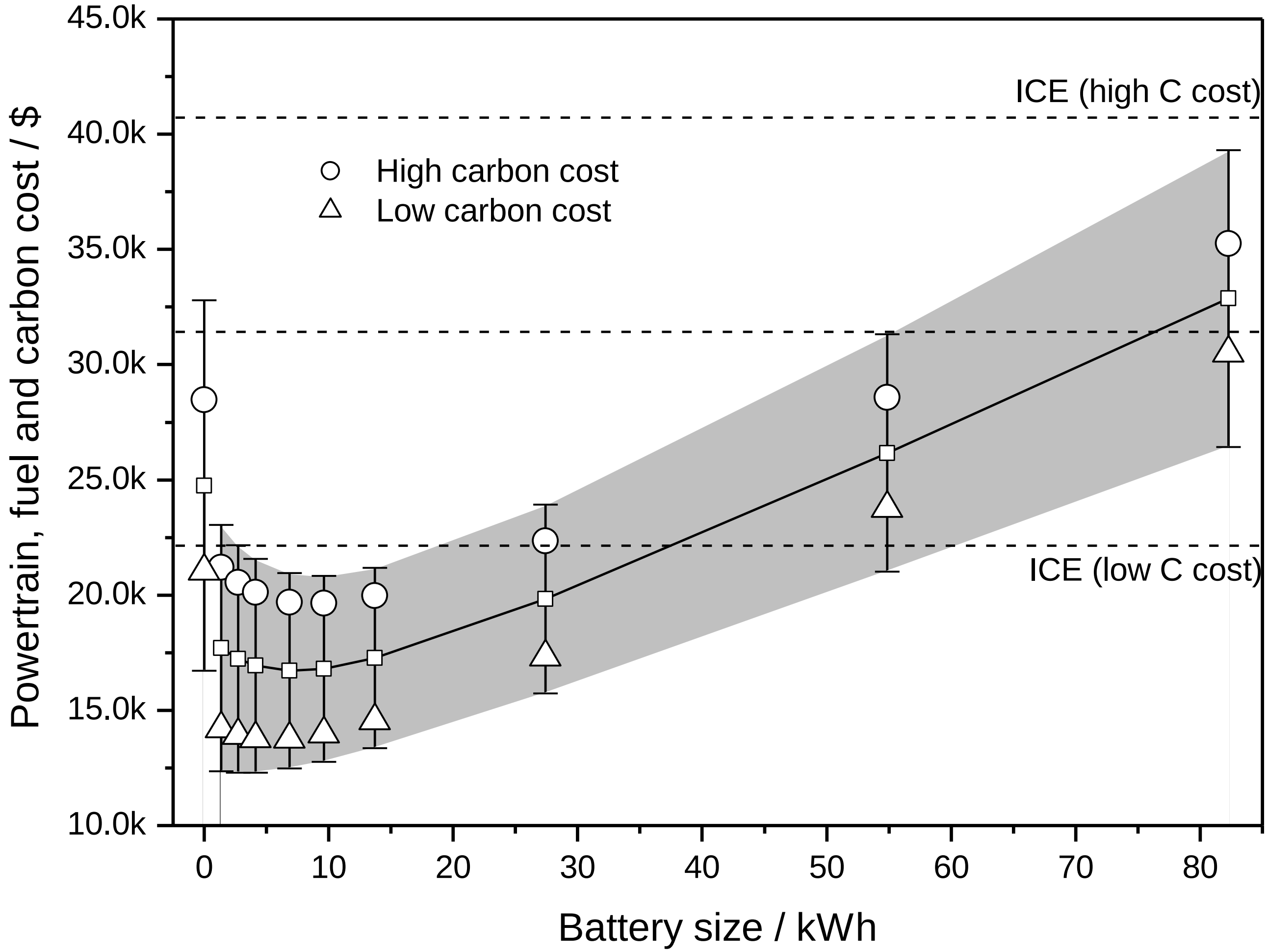
- FCEV
  - Highly sensitive
- FCHEV
  - Highly sensitive for small battery sizes
  - High cost favours larger battery size
  - For large battery size negligible effect



$$Cost = f\left(\left(C_{H_2}.C_E.C_{FF}\right)\left(C_{Batt}.C_{FC}.C_{ICE}\right)\left(B_{Size}.FC_{Size}\right).\left(C_{CO_2}.f\left(E_{Gen}\right)\right).\left(f\left(behaviour\right).f\left(vehicle\right)\right)\right)$$

Carbon price, affects comparison with ICE

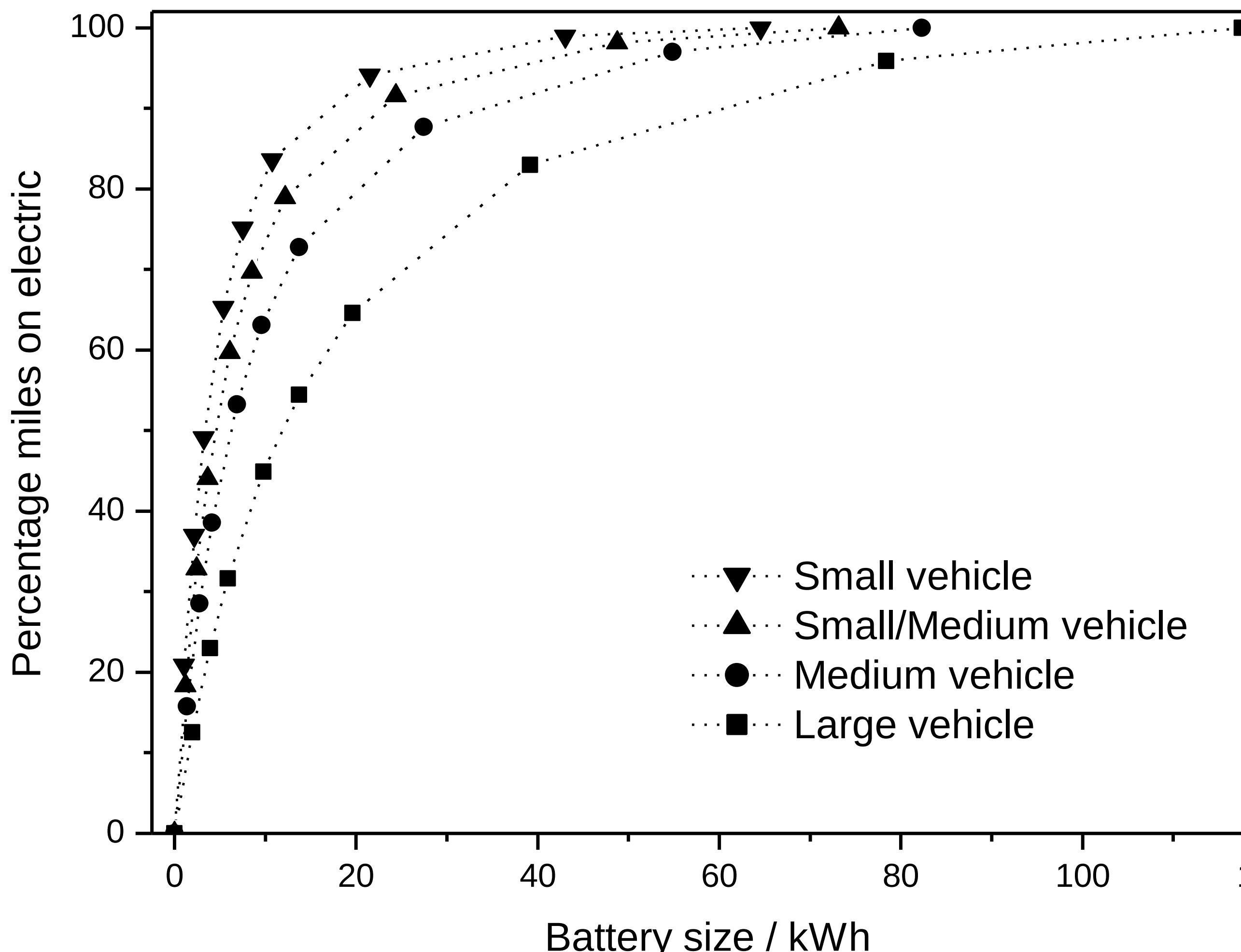
- FCEV vs FCHEV
  - Negligible effect
- FCHEV
  - Small favouring larger batteries because of H_2 production method
- ICE comparison
  - Highly sensitive
  - Effective carbon price necessary to favour new technologies
  - Both FCEV, FCHEV and BEV
  - Higher the better



$$Cost = f\left(\left(C_{H_2}.C_E.C_{FF}\right)\left(C_{Batt}.C_{FC}.C_{ICE}\right)\left(B_{Size}.FC_{Size}\right)\left(C_{CO_2}.f\left(E_{Gen}\right)\right)\left(f\left(behaviour\right).f\left(vehicle\right)\right)\right)$$

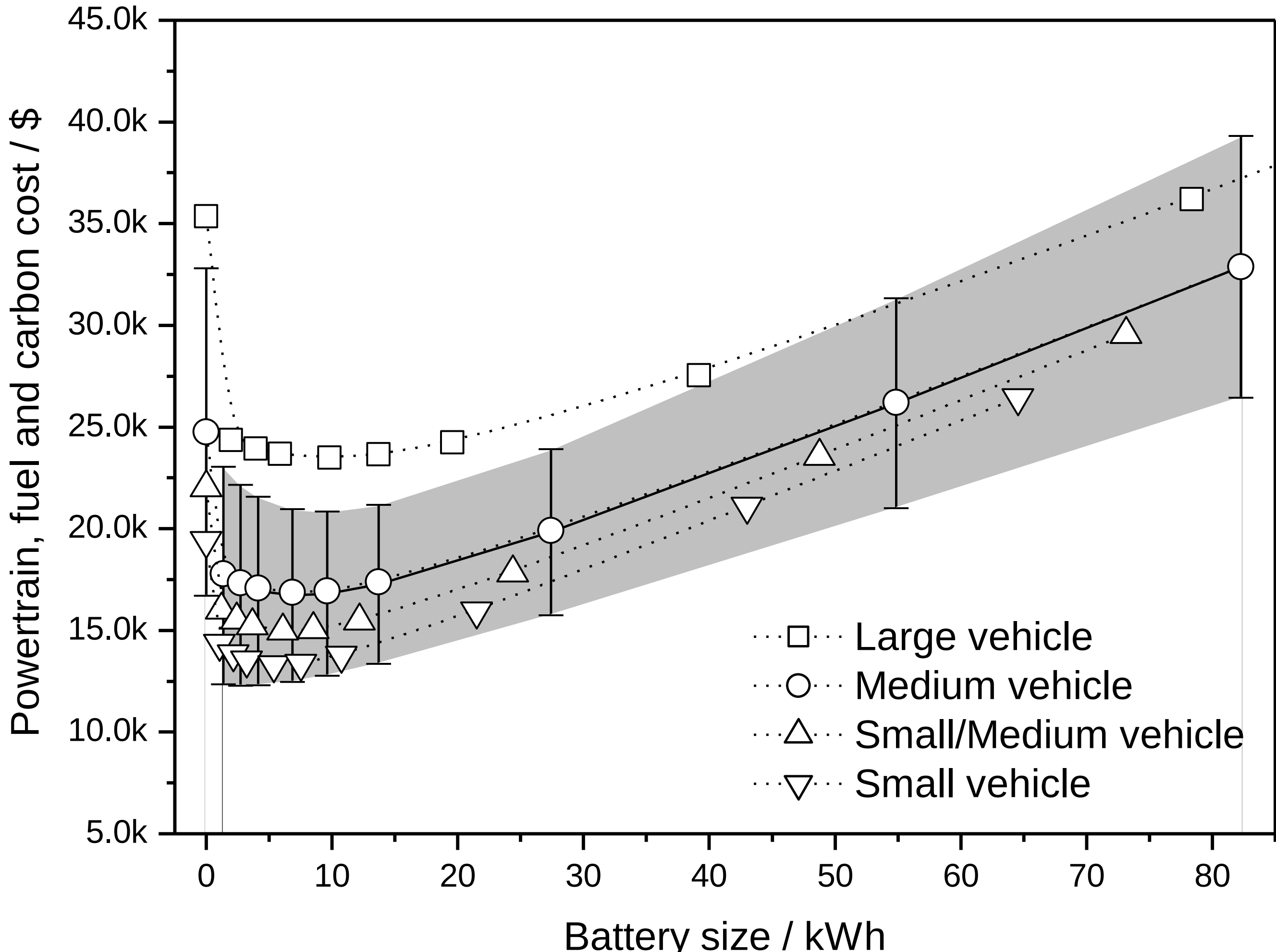
Different vehicle type – battery size

- Hybridisation
  - Sensitive to vehicle type
  - Large vehicles need large batteries
- Driving behaviour
  - Different for vehicle types
  - Increasing vehicle size increases total miles per day
- Effects
  - Both effects suggest increased costs and less benefit from the FCHEV
  - Large vehicle is clearly different



Different vehicle types, same battery size

- FCHEV
  - Similar optimum battery sizes predicted for all types
  - Electric range obviously affected
  - Large vehicle significantly different
- How does this affect emissions?

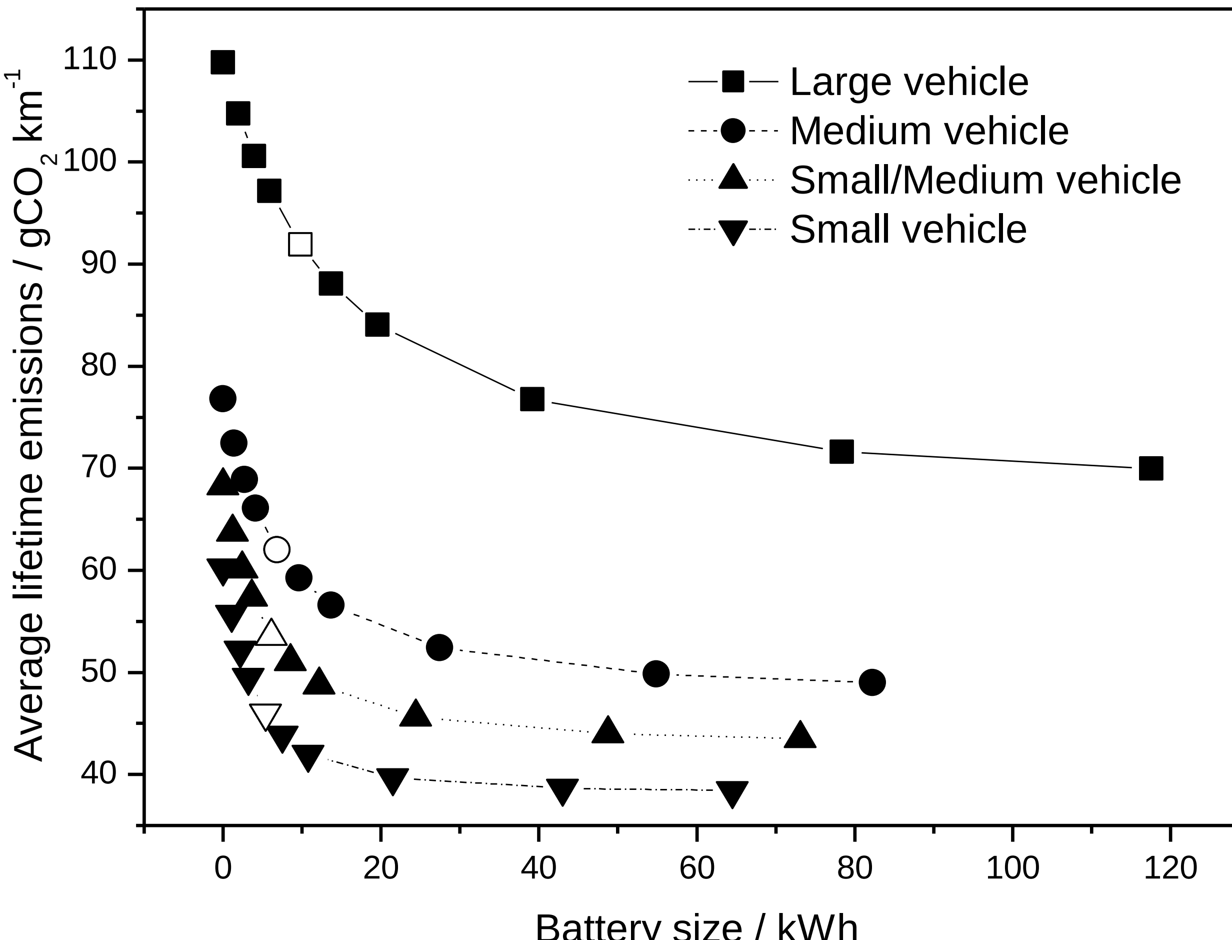


$$Cost = f\left(\left(C_{H_2}.C_E.C_{FF}\right)\left(C_{Batt}.C_{FC}.C_{ICE}\right)\left(B_{Size}\right)\left(FC_{Size}\right)\left(C_{CO_2}.f\left(E_{Gen}\right)\right)\left(f\left(behaviour\right).f\left(vehicle\right)\right)\right)$$

Dependent variable

Different vehicle type - emissions

- Emissions
  - Worse for larger vehicles
  - Not just effect larger energy consumption
- Economics
  - Favours similar battery size (hollow symbols)
  - But larger vehicle means less miles can be driven as electric
  - Increasing use of range extender



Note: This is for steam reformed methane and 50% decarbonised electricity

Conclusions

- FCHEV is cheaper than FCEV and BEV

- Battery sizes between **5-15 kWh** predicted independent of vehicle size or behaviour

- Vehicle size affects negatively
  - Percentage of miles driven on electricity
  - And CO_2 emissions
  - Because of both size and behaviour

- Reducing CO_2 emissions from electricity generation is crucial
  - Both to costs and emissions
  - But costs are dependent upon effective CO_2 emission pricing

- Example: Reducing CO_2 emissions from electricity generation by 50% and still using hydrogen from steam reformed methane in 2030
  - Would reduce emissions for the average vehicle from 192 $gCO_2\ km^{-1}$ for a petrol ICE to 62 $gCO_2\ km^{-1}$ for the cheapest FCHEV (a 68% reduction)