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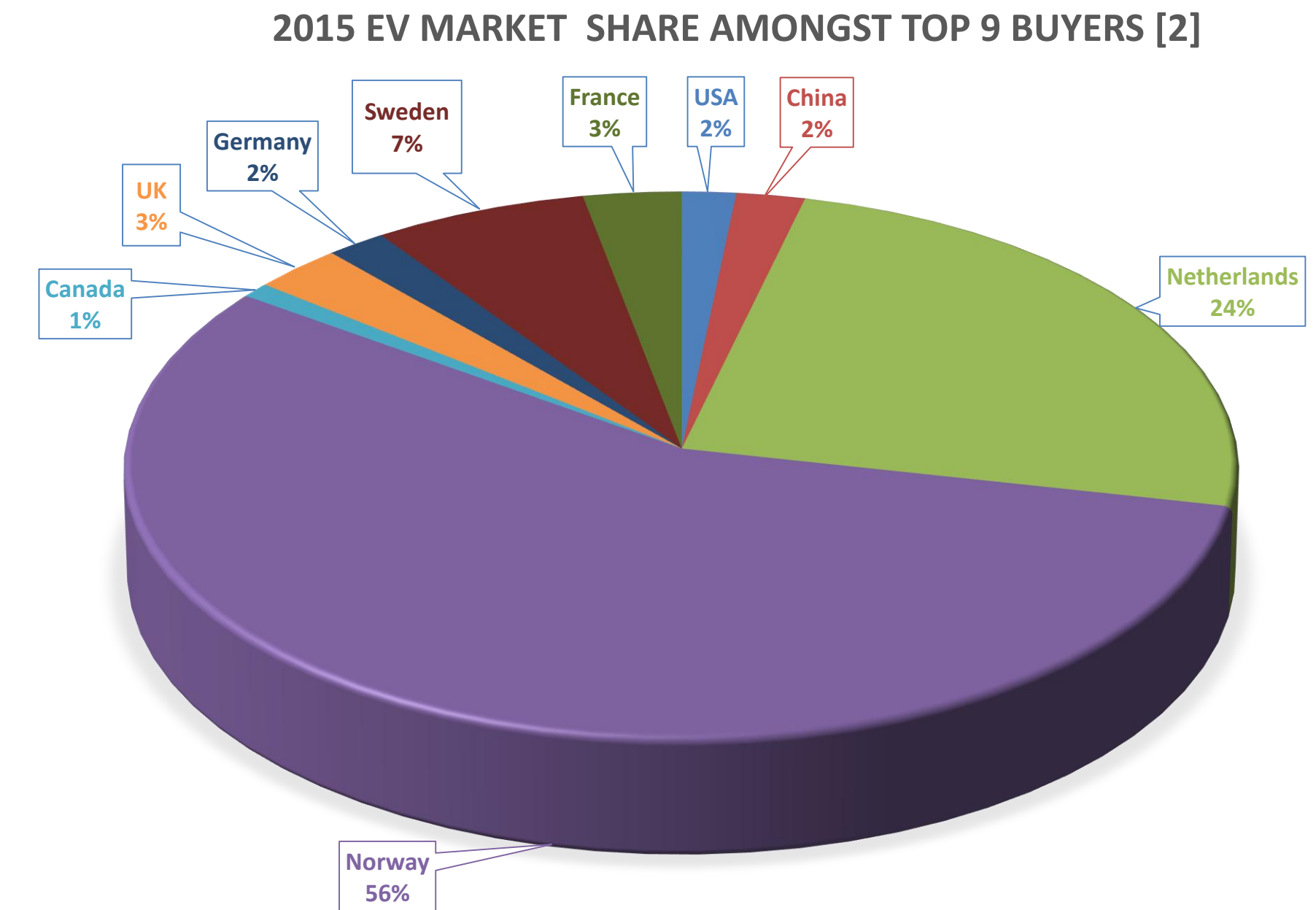
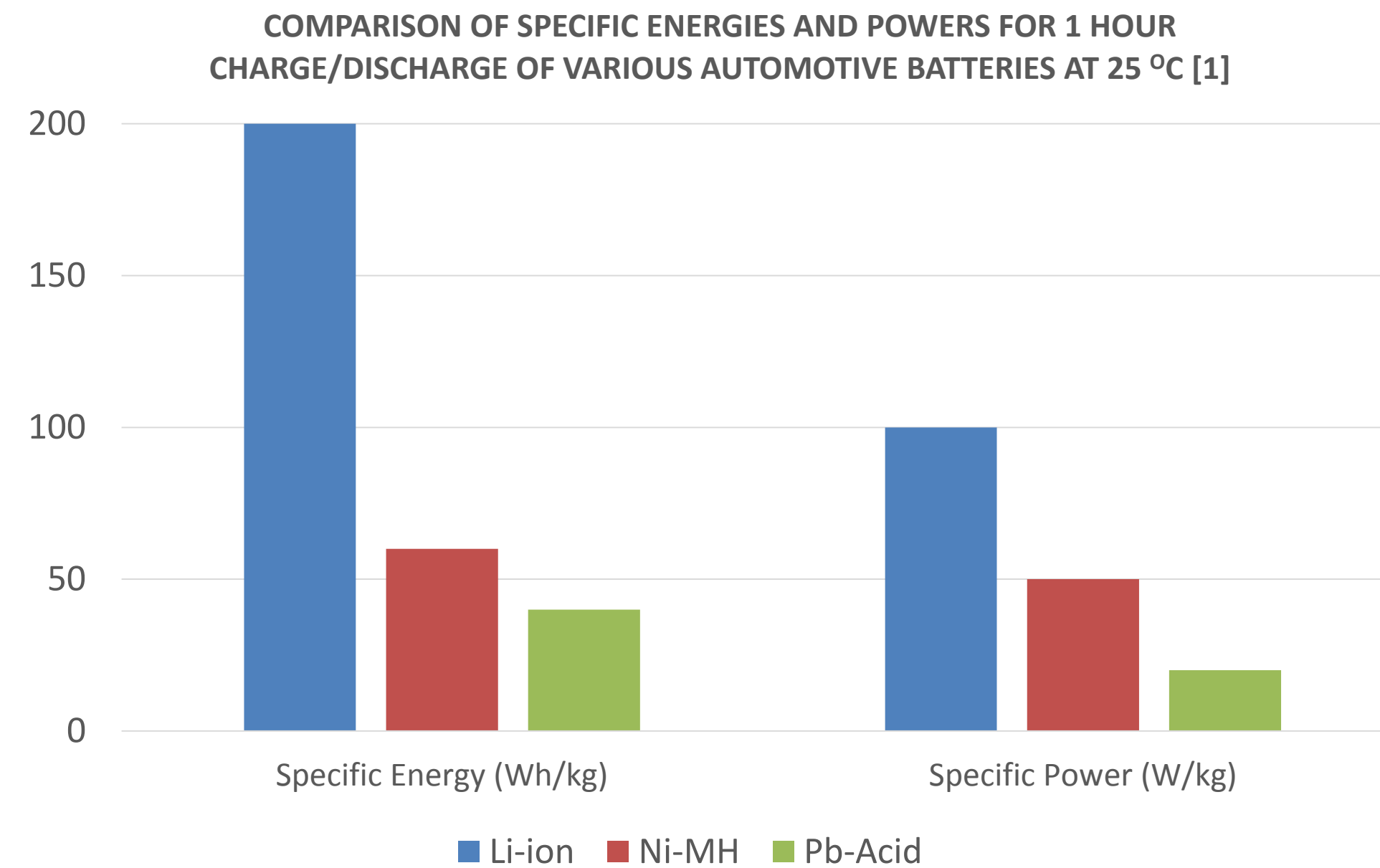
Low Temperature Performance of Lithium-ion Batteries for a Range of Drive Cycles

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LITERATURE BACKGROUND



- Ambient temperatures during winters in Norway, Canada, etc. can go down below -30 °C [2]
- EVs based on Li-ion batteries exhibit loss in driving-range and performance at subzero temperatures [3]
 - ✓ Capacity is indicative of driving-range while Power-capability is indicative of performance
 - ✓ At subzero temperatures, battery capacity reduces, internal resistance rises and risk of Li-plating increases [3]

[1] Conte, F.V., Battery and Battery Management for Hybrid Electric Vehicles: A Review. Elektrotechnik und Informationstechnik 2006. 123 (10): p. 424-431.

[2] Zahabi, S.A.H., et al., Fuel Economy of Hybrid-Electric versus Conventional Gasoline Vehicles in Real-world Conditions: A Case Study of Cold Cities in Quebec, Canada. Transportation Research Part D, 2015. 32: p. 184-192

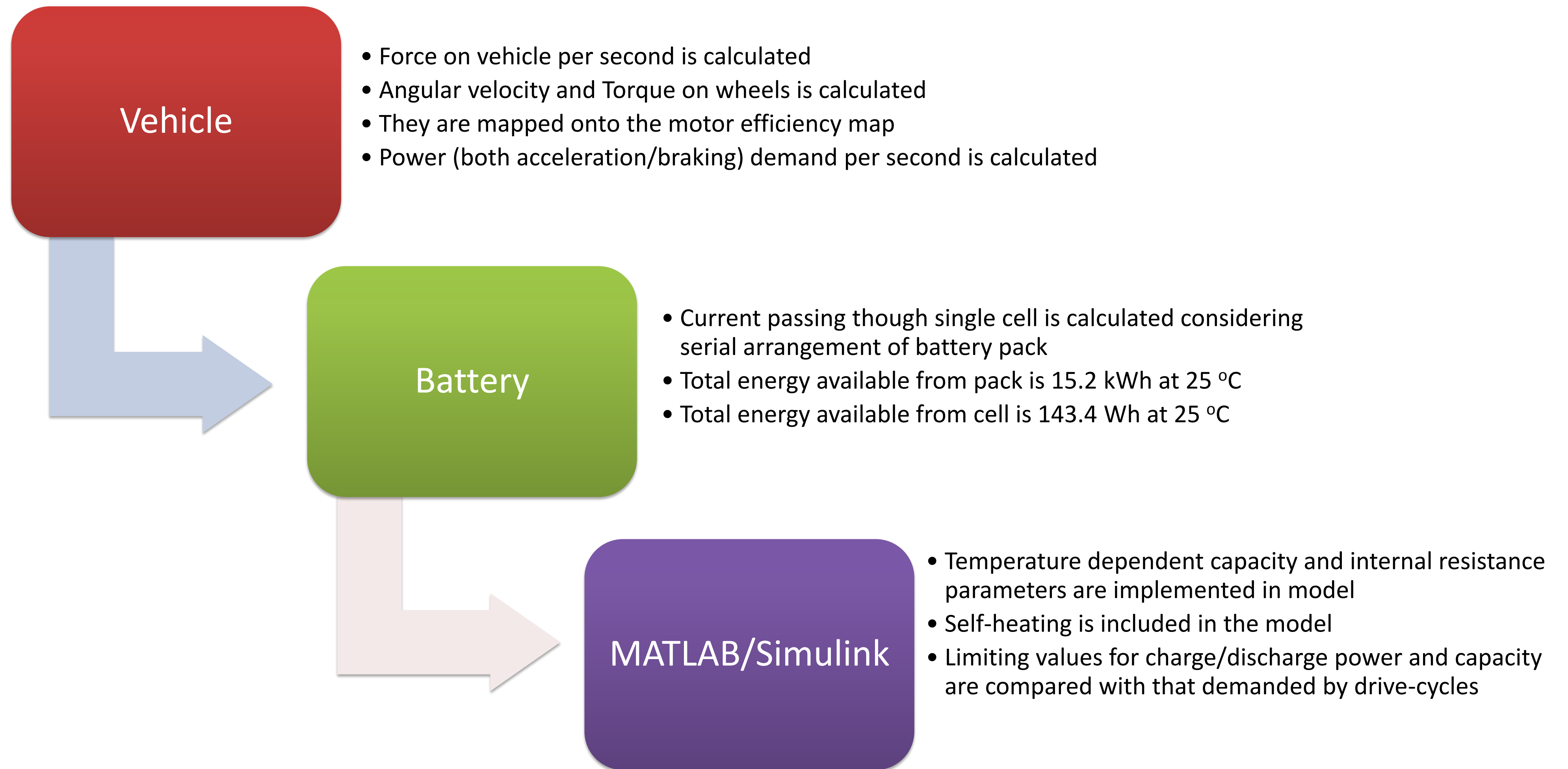
[3] Keil, P. and A. Jossen, Improving the Low-temperature Performance of Electric Vehicles by Hybrid Energy Storage Systems, IEEE Vehicular Power and Propulsion Conference (VPPC). 2014.



OBJECTIVES OF PAPER

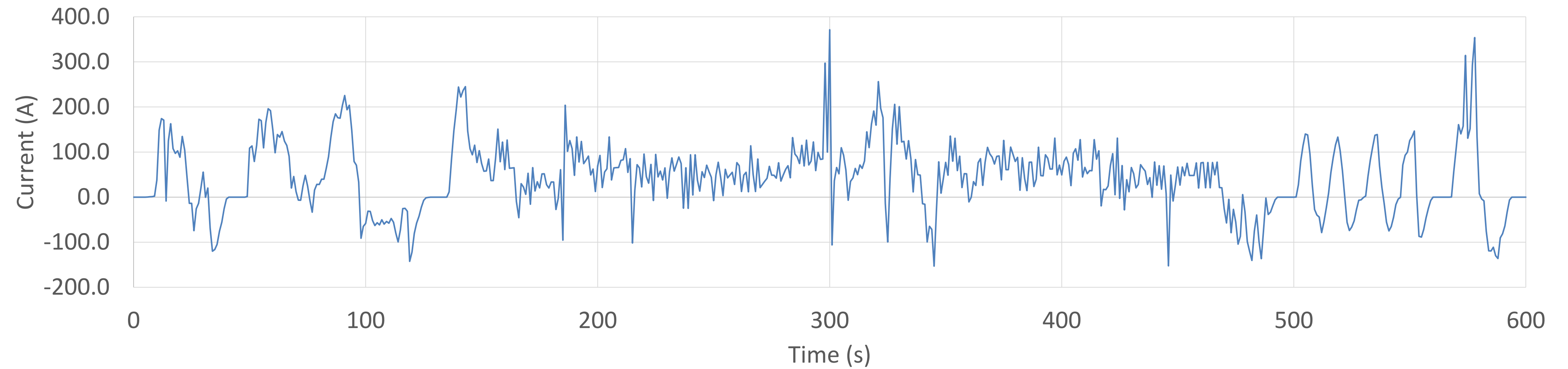
- To quantify deterioration in energy and power available from Li-ion battery
- To quantify minimum ambient temperatures where Li-ion battery meets energy and power demands of the following legislative drive-cycles for a typical BEV:
 - UDDS
 - FTP
 - NEDC
 - US06
- To show impact of regenerative-braking on driving-range and battery performance at subzero temperatures for above drive-cycles

METHODOLOGY



DRIVE CYCLE ANALYSIS

- Current Profile for US06:



- Energy and Power requirements of drive-cycles for 0% Regenerative-braking:

Drive Cycle	Energy Required (kWh)	Maximum Power (kW)	Maximum C-rate
FTP	3.30	47.56	3.3
NEDC	2.09	52.25	3.6
UDDS	2.19	47.56	3.3
US06	3.33	133.68	9.3



RESULTS AND DISCUSSION: VEHICULAR LEVEL

- Minimum temperatures where drive-cycles are met for 0% regenerative-braking from Energy perspective:

Drive Cycle	FTP	NEDC	UDDS	US06
Minimum Temperature (°C)	-17.0	-23.2	-22.6	-16.8

- Adding regenerative-braking leads to lesser energy being drawn from an Energy Perspective:

Drive Cycle	Minimum Temperatures (°C) if Battery has unlimited Power-capability for different Regenerative-braking efficiencies (%)			Maximum Energy drawn from Regenerative-braking (kWh)	Percentage of Energy demanded from Battery available from Regenerative-braking (%)
	100	50	0		
FTP	-21.6	-19.2	-17.0	0.92	39
NEDC	-25.2	-24.2	-23.2	0.38	22
UDDS	-26.4	-24.4	-22.6	0.63	41
US06	-20.4	-18.6	-16.8	0.71	27

- FTP and US06 cannot be met by battery below -16.8 °C from an energy perspective
- Regenerative-braking improves driving-range and lowers the temperature where drive-cycle can be met
- But, greater charging operations leads to higher risk of Lithium-plating that damages battery irreversibly



RESULTS AND DISCUSSION: CELL-LEVEL POWER PERSPECTIVE

- FTP, NEDC and UDDS are limited from an Energy-perspective for 0% regenerative-braking:

Drive Cycle	FTP	NEDC	UDDS	US06
MinE for 0% Regen (°C)	-17.0	-23.2	-22.6	-16.8
MinP for 0% Regen (°C)	-30.0	-30.0	-30.0	-12.1
MinP for 50% Regen (°C)	-4.2	-12.8	-12.4	-2.4
MinP for 100% Regen (°C)	-1.2	-8.4	-8.3	2.2

- Deterioration in discharge power is a limiting factor for the US06 only (Higher discharge C-rates)
- For the US06, Power is a greater limiting factor to battery performance than Energy
- Greater charging operations lead to significantly worse battery performance from Power perspective
- Charging operation typically not allowed to prevent Lithium-plating
- For aggressive drive-cycles, at low temperatures, battery has greater Power reduction than Energy decline
- Battery self-heating at lower temperatures improves battery power while compromising on driving-range
 - Managed self-heating strategies to improve low temperature battery performance will be heavily usage dependent



CONCLUSIONS AND FUTURE WORK

- Conclusions:
 - Vehicle performance limited below certain temperatures that are drive cycle specific:
 - From an energy perspective
 - From a power perspective only at high C-rates
 - Adding regenerative braking at low temperatures can increase vehicle range, but is detrimental to the battery
 - When charging power is accounted for, the drive cycles cannot be met at much higher temperatures
 - In order to increase vehicle range, a detailed understanding of cell behavior for varying levels of charging at low temperatures is required
- Future work:
 - Investigation of cell performance at low charge rates
 - Investigation of managing regenerative braking strategies with dynamic cell temperature



ANY QUESTIONS?