UTS UNIVERSITY OF TECHNOLOGY SYDNEY

The Complete Emissions Life Cycle Assessment of Electric Buses in the Australian Transport Sector

by Enoch Zhao

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Enoch Zhao, hereby declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Mechanical and Mechatronic Engineering, Faculty of Engineering and Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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I pour milk into my instant coffee mix before adding hot water because an Italian exchange student taught me that it prevents burning the coffee grounds. My default font is Times New Romans because my school used it back in 2001. I wanted to learn how to drive with three pedals, so for my first car I bought one with a manual transmission because James did the same several years before and "if he can do it, then so can I." He had to drive it home for me too. My wife once commented that I look good in black, therefore immediately after that comment I decided that I will be wearing the same colour for the next twenty-five years. And if I were to write down every one of the things my parents have taught me, from tying my own shoes to the philosophy of life, I suppose I could almost fill the world with books that would be written. Thus, I am a mosaic of the people I've ever met, even for the briefest moment.

In the same way, the completion of this thesis would not have been possible without the immense support, guidance, and assistance I have received. I had certainly enjoyed conducting research work and then writing this thesis. The lengthy page count is a good indicator that my love of writing could have launched me into a career as a novelist. But instead, by chance, I watched Iron Man 2 around the time I had to choose my year 11 subjects and I was so inspired (I blame you Robert Downey Jr.) that I decided to become an engineer instead. One thing led to another and now I have written my PhD thesis. So, as I compose each chapter of this thesis, I fondly reminisce the people who helped author this chapter of my life.

I would like to begin by thanking my principal supervisor, Dr Paul Walker, who from the start had opened doors and then mentored, encouraged, and trusted me as I completed my research. I am also immeasurably grateful to my co-supervisor, Dr Nic Surawski, for his invaluable insights and ongoing support. My special thanks to Scott Graham, Kevin Cook, Peter Bracken, Fatma Al-Widyan, Rami Haddad, and Peter Tawadros for their friendship and company. Special mention to Mighty Car Mods, FortNine, and Chris Fix.

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LIST OF PUBLICATIONS

Journal Articles

1. ***Zhao, E.**, May, E., Walker, P.D. & Surawski, N.C. 2021, 'Emissions Life Cycle Analysis of Charging Infrastructures for Electric Buses', *Sustainable Energy Technologies and Assessments*, vol. 48, pp. 1-14.

2. ***Zhao, E.**, Walker, P.D. & Surawski, N.C. 2021, 'Emissions Life Cycle Analysis of Diesel, Hybrid, and Electric Buses', *Journal of Automotive Engineering*, pp. 1-13.

3. ***Zhao, E.**, Walker, P.D., Surawski, N.C. & Bennett, N.S. 2021, 'Assessing the Life Cycle Cumulative Energy Demand and Greenhouse Gas Emissions of Lithium-Ion Batteries', *Journal of Energy Storage*, vol. 43, pp. 1-19.

Conference Papers

4. **^Zhao, E.**, Walker, P.D., Ong, A. & Al-Widyan, F. 2020, 'Measuring Road Conditions with an IMU and GPS Monitoring System', Asia-Pacific Vibration Conference (APVC) 2019, eds S. Oberst, B. Halkon, J. Ji & T. Brown, vol. 1, Springer, Sydney, Australia, pp. 95-101.

*Articles related to this thesis.

^Publications made during the PhD candidature but do not relate to this thesis.

NOMENCLATURE

ABS	Australian Bureau of Statistics
ABPS	Australian Battery Performance Standard
ADB	Asian Development Bank
AGCER	Australian Government Clean Energy Regulator
APRAA	Auto Parts Recyclers Association of Australia
ARENA	Australian Renewable Energy Agency
BEV	Battery Electric Vehicle
BOM	Bill of Materials
BNEF	Bloomberg New Energy Finance
BSE	Battery Storage Equipment
C	Carbon (Graphite)
CDP	Center for Disaster Philanthropy
CED	Cumulative Energy Demand
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
DAWE	Department of Agriculture, Water, and the Environment
DEE	Department of the Environment and Energy
DoD	Depth of Discharge
DPIS	Department of Planning, Industry and Science
EIA	U.S. Energy Information Administration
EoL	End of Life
EPA	Environmental Protection Agency
EPRS	European Parliamentary Research Service
ESS	Energy Storage System
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
GHG	Greenhouse Gas
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
L(R)	Lithium Rich
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCN	Lithium Cobalt Nickel
LCO	Lithium Cobalt Oxide
LCP	Lithium Cobalt Phosphate
LFP	Lithium Iron Phosphate
Li	Lithium
LIB	Lithium-Ion Battery
LMO	Lithium Manganese Oxide
LMR	Lithium Manganese Rich
LTO	Lithium Titanate Oxide
MftE	Ministry for the Environment
MoS_2	Molybdenum Disulphide
N_2O	Nitrous Oxide
NCA	Lithium Nickel Cobalt Aluminium Oxide
NMC	Nickel Manganese Cobalt
NOx	Nitrogen Oxides
OPC	Opportunity Pantograph Charger
OPR	Overhead Pantograph Rails
PEMS	Portable Emissions Measurement System
PHEV	Plug-In Hybrid Electric Vehicle
RDE	Real-World Driving Emissions
PM	Particulate Matter
S	Sulphur
SiC	Silicon Graphite
SiNT	Silicon Nanotube
SiNW	Silicon Nanowire
SoC	State of Charge
SOx	Sulphur Oxides
TfNSW	Transport for New South Wales
USyd	University of Sydney
WPT	Wireless Power Transfer

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ABSTRACT

Australia is increasingly experiencing the environmental impact of global warming. In recent decades, society has gradually become increasingly aware of the harm caused to the global environment by excess fossil fuel consumption. Greenhouse Gas (GHG) emissions and their contribution to global warming are considered to be one of the most pressing environmental issues of the present day. Transportation is the third-largest contributor of GHG emissions in Australia, contributing to 18.9% of total GHG emissions. Therefore, there are strong and urgent incentives to reduce emissions from the transportation sector. This problem can be rectified through the electrification of the vehicle's powertrain; consequently improving energy efficiency, reducing GHG emissions, and yielding a number of additional benefits. Thus, transitioning the transport sector to electrified powertrains have been perceived as the optimal solution to decarbonise the transport sector. This thesis employs a technique known as Life Cycle Assessment (LCA) to properly quantify and assess the environmental impacts from the transport sector.

First, this research starts by introducing Australia's development in the transition to electrified heavy-vehicle powertrains, the LCA technique, research objectives, and the outline of this thesis. Next, this research conducted a study that evaluated and calculated the magnitude of GHG emissions produced from the implementation of electric bus charging stations. Results show that the operations phase is heavily dependent on the electricity grid-mixes carbon intensity and contributes the most greenhouse gas emissions (98.8%), followed by production (0.69%), recycling and disposal (0.48%), installation (0.01%), and transportation (0.01%). Then, an evaluation of the environmental impact of electricity generation and four different charging methods was conducted. The study finds that the optimal charging arrangement is to deploy electric buses with small battery capacity in urban and suburban settings, large battery capacity in highway settings, and recharge with opportunity pantograph chargers or stationary charging stations. Moving on, an LCA was conducted to investigate the production, assembly, transportation, maintenance, and decommissioning phases of diesel, hybrid, and electric bus production. The results show that the electric bus has a higher total environmental impact than the diesel and hybrid bus (18.2% and 14.7% higher, respectively). After that, this research assessed LCAs of Lithium-Ion Batteries (LIBs) from various literature sources and found that the average global warming potential and cumulative energy demand from LIB production were 187.26 $kgCO_2e/kWh$ or 19.78 $kgCO_2e/kg$, and 42.49 kWh/kg, respectively. Finally, a summary and conclusion of this research as a complete entity concludes this dissertation.